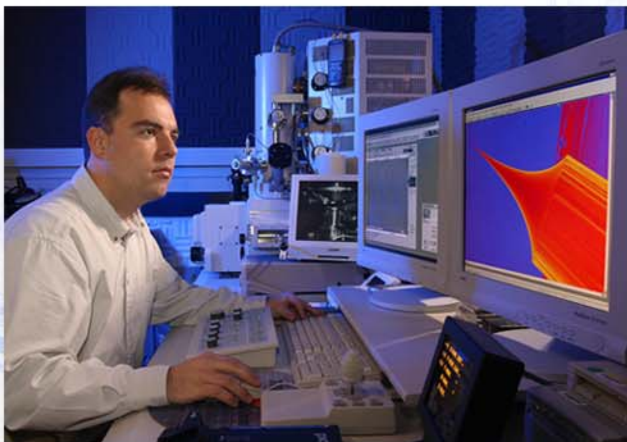
MEASURING FOR SUCCESS

The Programs of the Manufacturing Engineering Laboratory

January 2003



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Programs of the Manufacturing Engineering Laboratory

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Abstract

The National Institute of Standards and Technology's Manufacturing Engineering Laboratory (MEL) strengthens the U.S. economy and improves the quality of life by working with the U.S. manufacturing industry to develop and apply infrastructural technology, measurements, and standards to meet their needs. This report contains summaries of MEL programs that support the needs of the U.S. manufacturing industry. Each program summarizes the resources, objectives, customer needs that are addressed, accomplishments, current year plans, lifetime objectives, and related measurement and standards work.

Keywords

Manufacturing, manufacturing engineering, technology, measurements, metrology, standards

Disclaimer

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DIRECTOR'S MESSAGE

Dale Hall, 301 975 3400, dale.hall@nist.gov

MEL had an excellent year in 2002, making solid technical accomplishments and taking a number of management actions that should position us well for the future. The technical work described in this book addresses the critical measurements, standards, and advanced technology needs of our manufacturing customers and contributes to the development of the measurements and standards infrastructure that will be needed in the emerging technology areas of the future. The book recounts the technical progress made in 2002 and describes our programs for 2003. This year's new format incorporates several suggestions from our customers to make it more useful as a source of information on our laboratory and its programs.

NIST completed a strategic plan this year that identified four future technical focus areas: nanotechnology, information technology/knowledge management, homeland security, and health care. MEL is a technical contributor in all of these areas, most substantially in the first two. Our Operational Plan for 2003, which is available upon request, describes how we will make progress in those areas while maintaining our commitment to US manufacturers in established industries by providing key technical products and services.

This year, we began or advanced a number of bold strategic initiatives to enhance MEL's role and visibility in the manufacturing community and to increase the synergy of manufacturing-related programs within NIST:

- Under MEL leadership, the six federal agencies in GATE-M – the Government Agencies Technology Exchange in Manufacturing – came together to define areas of mutual interest and cooperation and to provide a broad government perspective on manufacturing technology issues. The bottom line will be a more coordinated federal government effort in manufacturing.
- MEL is sponsoring a national, policy-level Manufacturing Forum to be held in March 2003. This Forum, which will be conducted under the prestigious auspices of the National Academies, will identify and propose actions to address key manufacturing issues and raise the

visibility of manufacturing as a key component of our economic vitality and national security. MEL expects to use the results of this forum as a key element in its strategic planning.

- MEL has also taken the lead in working with other NIST units to develop and propose a more assertive, higher-profile position for NIST in the broadly defined area of manufacturing.
- As part of our determination to leverage our limited resources for the benefit of industry, we are aggressively exploring external research alliances with companies, universities, and industry groups.

In November, the President signed into law the Enterprise Integration Act of 2002, which calls upon NIST to "work with major manufacturing industries on an initiative of standards development and implementation for electronic enterprise." This bill, which had strong industry support, addresses a crucial business and technical issue on which MEL has a long history of leadership. If a corresponding appropriations bill is passed and signed, MEL stands ready to expand our work and our collaborations both within NIST and externally in systems interoperability and enterprise integration.

I am pleased to note that it is now certain that several of our most demanding metrology programs will move into the new NIST Advanced Measurements Laboratory in 2004. This new, $200 million facility will give us an unparalleled environment for state-of-the-art dimensional and mechanical metrology and will ensure our continued ability to provide customers with the best available measurement technology.

In closing, I return to the outstanding technical work of our staff and our collaborators. This year I met with every MEL technical program and group for informal reviews, beginning a regular, continuing series of technically focused meetings to discuss our technical progress and future measurement challenges. The reviews, which were a personal pleasure for me, reinforced to me the breadth, importance, and superb technical quality of our work as well as the creativity and dedication of our staff. The needs of our customers are embedded into our programs from their onset, and we remain committed to providing customer value as well as the highest technical quality. We like to hear from our customers, and I encourage you to help us understand your needs better.

Dale Hall

INTRODUCTION AND USER'S GUIDE

Promoting a healthy U.S. manufacturing economy by solving tomorrow's measurement and standards problems today

The National Institute of Standards and Technology (NIST) Manufacturing Engineering Laboratory (MEL) is pleased to present a summary of its technical programs for fiscal year (FY) 2003. MEL's mission is to satisfy the measurements and standards needs of U.S. manufacturers in mechanical and dimensional metrology and advanced manufacturing technology. We do this by performing research and development (R&D), providing services, and participating in standards activities. Our long-term goal is best summed up by the Laboratory's core purpose — to promote a healthy U.S. manufacturing economy by solving tomorrow's measurement and standards problems today.

With a value-added contribution of $1.5 trillion, U.S. manufacturing — our customer base — directly accounts for approximately 16 percent of the U.S. gross domestic product, and its products are vital to other key sectors of the economy. We serve the manufacturing sector of the U.S. economy in a broad sense, working with partners from industry as well as other government agencies and academia to develop the measurement tools and infrastructure that enable higher productivity, new products, and improved processes. Our work primarily supports the manufacture of durable goods, including discrete, mechanical, and electromechanical products. We also exploit opportunities to apply our technology to support other key industrial sectors, including the manufacture of non-durable goods and non-discrete products. Our customers span the full range from established to emerging-technology industries, including automotive, aerospace, construction equipment, electronics, optics, telecommunications, and nanotechnology. MEL also provides design and fabrication services to other NIST operating units through its Fabrication Technology Division.

MEL actively develops and maintains strong relationships with its customers and stakeholders. In fact, many of the nation's leading manufacturers rely on MEL; therefore, we develop and operate programs in direct response to their needs. Working collaboratively with our partners, our staff members solve measurement and standards problems that allow our industrial customers to take full advantage of technology such as advanced manufacturing techniques and on-line quality assurance processes. Our customers depend on MEL for calibration services that are the best in the world. These services, for example, ensure dimensional compatibility of items manufactured at different sites and satisfy requirements for traceability to national standards. MEL maintains an active program of technology transfer through cooperative research, industrial research associates who come to our laboratories, publications, conferences, seminars, workshops, and customer visits. MEL's interactions extend from the bench researcher to senior management.

During 2002, MEL staff continued to serve our customers in other important ways. The measurement methods, calibration services, software interface standards, and leading-edge manufacturing techniques all support U.S. industries' efforts to improve performance and provide quality products in the laboratory, the design shop, the factory, and ultimately, in the marketplace.

Our technical work is carried out through strategic programs as well as division or special projects. This document summarizes those efforts and is organized as follows.

Division Overviews (starting on page 7) – MEL comprises five divisions that are responsible for specific mission areas that address the complexity and demands of the manufacturing community:

- Precision Engineering Division provides the foundation for dimensional measurements over 12 orders of magnitude (hundreds of meter to nanometers);
- Manufacturing Metrology Division fulfills the measurements and standards needs in mechanical metrology and advanced manufacturing;
- Intelligent Systems Division focuses on the measurement, standards, development and application of intelligent control, open-architecture standards, and intelligent systems manufacturing;
- Manufacturing Systems Integration Division promotes U.S. economic growth by working with industry to develop and apply measurements and standards that advance information-based manufacturing technology; and
- Fabrication Technology Division provides world-class instrument and specialized fabrication support for NIST researchers and serves as a testbed for many NIST and MEL programs.

Divisions are organizational units that are ultimately responsible for long-term responsibilities (e.g., maintaining specialized equipment, meeting staffing needs, and developing and maintaining core technical competencies.) While each division has its own focus, collaborations between divisions are commonly used to achieve MEL strategic program goals. **A chart highlighting the contributions of each division to specific MEL Programs can be found on page 44.**

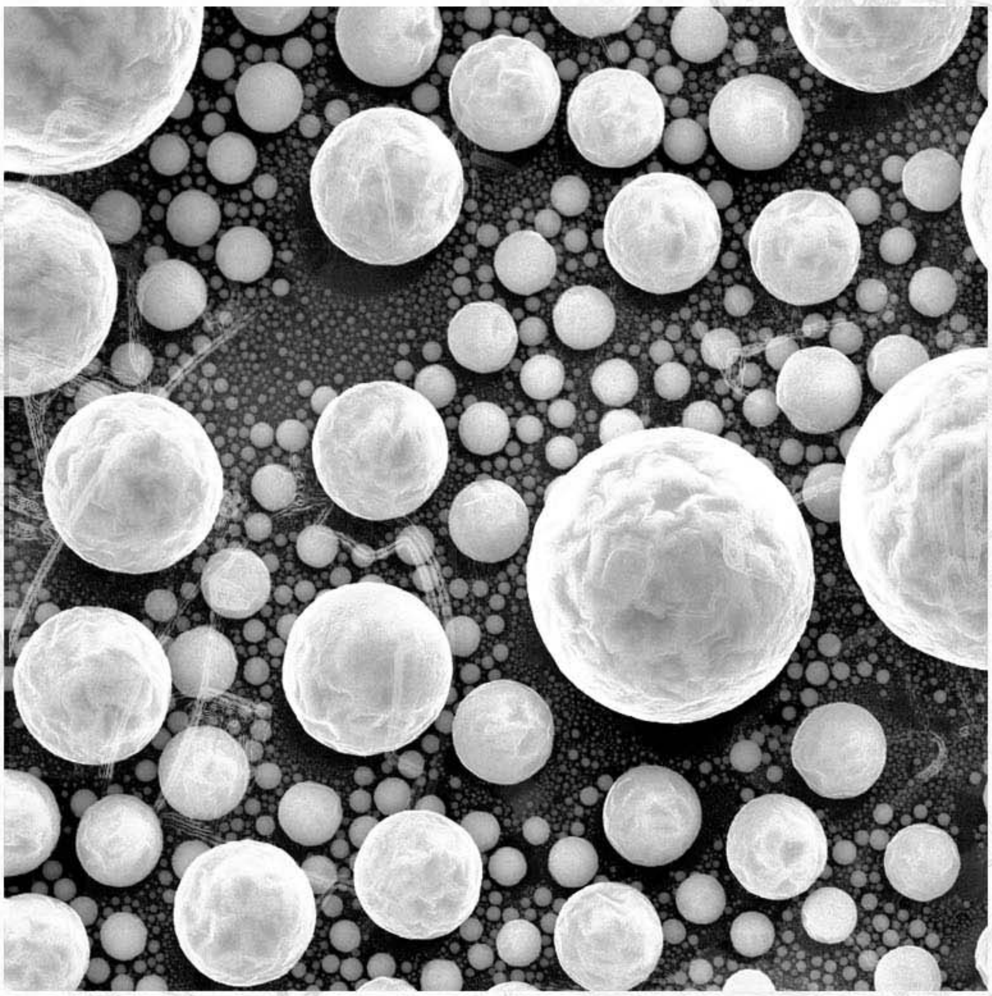
Program-at-a-Glance (starting on page 25) – These one-page, high-level descriptions provide a quick overview of each technical program, including the goal, a problem statement, technical approach, and customers and collaborators.

Program Descriptions (starting on page 45) – MEL's programs focus on measurement and standards for making things traceable, right, small, and interoperable. Our programs address advanced manufacturing research and measurement services in dimensional and mechanical metrology, manufacturing processes and equipment, systems integration and interoperability, and intelligent controls. Within the program's 5-year planning horizon, milestones or technical objectives are set to help achieve the program goal. This section provides comprehensive descriptions of each of MEL's 18 FY 2003 programs, including its goal, customer needs, technical approach, program objectives, technical outputs, and accomplishments of the past year.

Special Programs & Projects (starting on page 161) – In addition to MEL strategic programs, MEL staff work on exploratory projects and participate in an international program designed to increase U.S. manufacturing competitiveness.

Appendix (following page 172) — This section provides a list of commonly used acronyms for quick reference.

Divisions



PRECISION ENGINEERING

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Mission and Responsibilities

Providing the foundation of dimensional measurement that meets the needs of the U.S. industrial and scientific communities

The mission of the Precision Engineering Division (PED) is to provide the foundation of dimensional measurement that meets the needs of the U.S. industrial and scientific communities by conducting research in dimensional measurements, developing measurement methods, providing measurement services, and disseminating the resulting technology and length-based standards.

The PED's mission reflects our responsibility to perform four core functions: research, development, measurement services, and information dissemination. Each core function includes a variety of processes that serves numerous customers, collectively identified as industrial and scientific communities, both public and private. The division's research and development addresses precision-engineered, length-metrology-intensive systems in both measuring and production machines.

The PED delivers to industry important length-related measurements, standards, and technology services that support U.S. manufacturing's products and processes. Feature dimensions of interest range in size from multiple meters to the sub-nanometer level. Framed and frameless, general and special-purpose measuring probes, machines, and systems measure these features. Measurement tools make use of the full spectrum of optical, mechanical, electrical, and quantum-mechanical phenomena. Measurements are tied to the Systeme Internationale (SI) unit of length (modernized metric system) by means of stabilized lasers and displacement interferometry.

Resources

The division is organized into four groups, each of which is vertically integrated from research through services within a domain specified by the scale of measurement features addressed and the measurement technologies employed and served.

The Large-Scale Coordinate Metrology Group concentrates on measurements in the range of 1 meter or larger. Measurements are made by coordinate measuring machines and frameless coordinate length-metrology systems involving mechanical-probe, laser-ranging, theodolite, and related interferometric systems.

The Engineering Metrology Group concentrates on measurements in the range of 1 millimeter to 1 meter. These measurements are often of complex shapes, such as turbine blades, threaded fasteners, and gears.

Special-purpose coordinate measuring systems are used to obtain these measurements.

The Surface and Microform Metrology Group concentrates on measurements in the range of 1 micrometer to 1 millimeter where surface roughness and microform are critical. Measurements are made by tunneling microscopes, mechanical profilometry, phase-measuring interferometry, and related techniques.

The Nanoscale Metrology Group concentrates on measurements in the range of 1 nanometer to 1 micrometer. Tunneling, atomic-force, electron, and visible- and ultraviolet-light microscopes are used to obtain these measurements. The group places special emphasis on satisfying the advanced needs of U.S. microelectronic manufacturing industries.

Among PED's advanced measurement facilities are

- the NIST Line Scale Interferometer, which provides "Best-In the-World" SI-traceable one-dimensional (1D) measurement over a sub-micrometer to meter range;
- Molecular Measuring Machine or M-Cubed, an experimental two-dimensional (2D) measuring machine capable of measuring the placement sub-nanometer features with sub-nanometer resolution;
- M48 Coordinate Measuring Machine (CMM), a three-dimensional (3D) mechanical-contact and vision-based measuring machine for the calibration of 1-, 2- and 3-D reference standards to sub-micrometer accuracies; and
- a calibrated indoor target and outdoor monument systems for the short- and longer range characterization and calibration of theodolite, laser tracker, photogrammetric and Global Positioning System (GPS)-based coordinate measurement systems.

Program Involvement

Our staff members participate in programs at the division, laboratory, and NIST levels. We lead the following division-level programs: Large-Scale Metrology, Engineering Metrology, Surface Metrology, and Nanometer-Scale Metrology. We also lead the Shop Floor as a National Measurement Institute (NMI) program, which has a broader, MEL-level focus. We participate in other laboratory-level programs, including Integrated Nano-to-Millimeter Manufacturing Technologies and Predictive Process Engineering. We also participate in NIST-wide programs such as the National Semiconductor Metrology Program and the Advanced Technology Program.

In addition to conducting research and providing services within the five MEL programs for which we have principal responsibility, PED invests in the long-range development of new capabilities and improvement of its basic metrological capabilities. As with our programs, these activities span the range from the large-scale, through the mid-sized scale, to the nano-scale.

At the large-scale, the PED invests in techniques for the error-mapping of a special-purpose industrial large-volume CMM; training in the application of advanced surfacing software for CMM and optical coordinate measurement systems; testing of a prototype large-scale calibration artifact; and participation in collaborations on large-scale metrology with other national metrology institutes (NMIs).

At the mid-sized scale, the PED invests in developing an in situ differential-deformation technique that will serve to reduce the number of masters required in calibrations of gage blocks of various materials; a new capability to perform state-of-the-art cylindricity measurements by enhancing a late-model, high-performance cylindricity measuring machine; and a new capability to perform state-of-the-art 2D measurements of coordinate position by acquiring and enhancing a late-model, high-performance 2D measuring machine.

At the nanoscale, the PED invests in improving the geometry and sensing of our current linescale interferometer system to ensure that we can continue to perform state-of-the-art 1D calibrations; establishing the basis for future state-of-the-art 1D measurements by testing of the elements of the conceptual design of a next-generation linescale interferometer; and pursuing the development of a scanning tunneling microscope (STM)-based planar CMM with atomic resolution.

In addition to developing instrument-based laboratory capabilities, we also invest in the intellectual and operational infrastructure associated with these capabilities. These activities include participation in seven planned, ongoing, or recently completed international key comparisons; participation in Bureau International des Poids et Mesures (BIPM committees), ISO, and U.S. national standards committees on metrology, including the international Joint Committee for Guides in Metrology and the BIPM Director's Advisory Group on Measurement Uncertainties; and the provision of on-line calibration-service-enhancing information, including customer-order status reporting and a website tool box for calibration-related calculations.

Manufacturing Metrology

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Fulfilling the measurements and standards needs of the United States in mechanical metrology and advanced manufacturing technology

Mission and Responsibilities

The mission of the Manufacturing Metrology Division (MMD) is to fulfill the measurement and standards needs of the United States in mechanical metrology and advanced manufacturing technology by

- research and development (R&D) aimed at realizing and disseminating SI mechanical units; developing methods, models, sensors, and data to improve metrology, machines, and processes;
- providing services in mechanical metrology, machine metrology, process metrology, and sensor integration; and
- leading the development of national and international standards.

The division acts as the nation's reference laboratory for the mechanical metrology units of mass, force, acceleration, sound, and pressure. Our commitment to this responsibility involves many facets:

- realizing, maintaining, and improving the primary standards for these quantities;
- conducting intercomparisons and other studies to coordinate and establish comparability of these standards to those of other countries;
- providing the States' Weights and Measures Laboratories traceability to these standards;
- developing suitable mechanisms to enable the transfer of accurate measurement capabilities to customers in the field and secondary calibration laboratories; and
- providing efficient test and calibration services of the highest quality.

Examples of our work include the calibration of special artifacts such as prototype kilograms, including subdivisions and multiples of this unit, and testing and calibration of instruments and devices such as load cells, proving rings, microphones, hearing aids, and accelerometers. Typically, we perform more than 3000 standard tests and calibrations each year.

We continually strive to improve these measurement services by conducting ongoing R&D to investigate new ways of performing measurements. R&D can lead to new types of measurements for the provision of services for new quantities (e.g., torque) or for new ranges of measurements (e.g., micro-forces), the new realization of a unit (e.g., Watt-based kilogram), and new measurement methods and data for industrial product development (e.g., loudspeakers and hearing aids).

In addition to our mechanical metrology work, the Division has a parallel and integrated focus on meeting the special measurement and standards needs of U.S. manufacturers in advanced manufacturing technology. To provide the context for efficient development of manufacturing metrology methods, we explore advanced manufacturing processes and machines to support U.S. industry's need to improve productivity, tighten tolerances, and machine new materials. Areas of manufacturing technology now being studied include: high-speed milling, high strain rate materials properties, diamond turning, advanced optical fabrication and metrology, metrology for machining meso-scale parts, smart sensors for machine/process monitoring and control, and machine tool and subsystem characterization.

Crosscutting the Division's work in mechanical metrology and manufacturing technology are projects in sensors, interfaces, and networks for distributed measurement and control technologies and efforts to provide leadership at national, regional, and international standards organizations.
The goal of the standardization efforts is to use the foundation of rigorous metrology established in our programs to work with industry in formulating and developing documentary standards that embody strong representation of U.S. interests and technology. The division led, participated in, and made major contributions to key international comparisons and over 60 standards committees and working groups during this past year.

Additional activities address the maintenance and development of short-term and long-term core competencies in technical areas crucial for the effective accomplishment of the division's mission and function. We focus on building competencies in the areas of measurement service automation, statistical analysis of experiments and data, uncertainty in measurements, thermometry measurements, reliability and maintenance engineering, instrumentation and data acquisition, and signal processing and analysis. Over the past year, we have trained several staff members to provide additional support for our calibration services in mass metrology, vibration metrology, and acoustical metrology.

Resources

Staff

The division has a strong team of scientists, engineers, technicians, and support staff, including post-doctoral fellows, full-time guest scientists (NIST Associates), and part-time students.
The division has a total staff of about 45 full-time equivalents. The staff has expertise and skill in applied mathematics, acoustics, applied mechanics, optics, computer science, electrical engineering, electroacoustics, mechanical engineering, materials science, mechanics, metallurgy, and physics.
In addition to these areas, we have specialists in advanced communication protocols, closed-loop process control, computer aided design and drafting, computer integrated manufacturing, database and knowledge base development, design and development of microprocessor-based electronic systems, distributed measurement and control systems, in-process inspection and statistical process control, networked smart transducers, machine dynamics, machine tool metrology, microprocessor-based sensor development and interfacing,

network technologies, object-oriented modeling, precision mechanical and electrical instrumentation, sensor-based machine systems, single point diamond turning, signal processing, and ultrasonics.

Facilities

Mass: A state-of-the-art class 1000 clean room with a high level of temperature and humidity control houses comparators that enable kilogram comparisons to the national prototype kilogram to a combined standard uncertainty of less than 20 µg and ten kilogram comparisons to a combined standard uncertainty of less than 200 µg. The mass laboratories house a total of 20 balances that provide the capability for mass measurements over the range from 1 mg to 1100 kg and a platform scale for mass measurements up to approximately 28,000 kg. Three of these balances also enable us to provide magnetic susceptibility and solid density measurements of mass artifacts.

Force: Six thoroughly characterized dead weight machines with capacities of 2.2 kN, 27 kN, 112 kN, 500 kN, 1.334 MN, and 4.5 MN provide a capability to realize force over the range from 44 N to 4.5 MN with a relative combined standard uncertainty of 5 x 10^{-6}. An additional hydraulic-based system permits force measurements up to 54 MN. Facilities have been developed that permit certification of prototype force transducers in accordance with requirements of the National Type Evaluation Program. We have a new facility to measure the immunity of load cells to electromagnetic fields.

Acceleration: We developed four measurement systems that produce highly linear, unidirectional, sinusoidal motion excitation of test and/or reference accelerometers in which the displacements or accelerations are measured by a fringe counting interferometer, fringe disappearance interferometry, or reciprocity methods. This combination of instruments permits measurements and calibrations of accelerometer sensitivity relative to a NIST reference standard unit to an estimated expanded uncertainty of 1% to 4% over a frequency range of 1 Hz to 20 kHz and, depending on the frequency range, accelerations of 0.02 g to 200 g.

Acoustical measurements: Three anechoic chambers, one with a volume of 450 m^3, are available for measurements and calibrations of loudspeakers, microphones, and hearing aids. Pressure response levels of customer microphones are obtained from comparison calibrations using two NIST standard reference microphones. Typical expanded uncertainties for pressure calibrations of customer microphones are less than 0.25 dB over a frequency range of 50 Hz to 17 kHz. Free-field response levels of customer microphones are obtained by the reciprocity technique.

Optical testing: Three facilities are available for optical testing work. The X-ray Optics Calibration Interferometer (XCALIBIR) facility houses a next-generation visible wavelength interferometer for measuring surface figure error of precision optics with a measurement capability target of 0.25 nm RMS expanded uncertainty for flats, spheres, and mild aspheres at the nominal aperture of 300 mm. XCALIBIR is a state-of-the-art environmentally controlled facility.

An optics metrology laboratory contains a second visible wavelength interferometer used to measure optics up to 150 mm in diameter. This laboratory also has an infrared interferometer for measuring thickness, thickness variation, and bow of semiconductor wafers up to 300 mm in diameter.

A microscopy laboratory contains equipment to perform polarized light microscopy and surface finish measurements to support development of subsurface damage (SSD) assessment methodologies.

Sensor interfacing and networking: The smart transducer interface laboratory is equipped with microprocessor development systems for embedded devices development and Microsoft Windows NT-based system development tools. This lab provides an integrated environment for conducting research, testing, validation, and application development on smart transducer standard interfaces, and Intranet/Internet-based distributed measurement and control systems.

Manufacturing technology: Our Division has four machining laboratories. One laboratory has 0.5 K temperature control and houses a commercial three-axis, diamond turning machine with an air bearing spindle and laser feedback position control to 10 nm resolution in x (0.4 m) and z (0.2 m); the third axis is a 360 degree rotary axis.

A second laboratory provides vibration isolation and acoustical shielding for three machines, two of which are two-axis [x =0.5 m, z =0.25 m] machines with air bearing spindles. These machines are used for orthogonal machining experiments to measure cutting temperatures and other projects. There is also a conventional lathe primarily used for cutting experiments for the assessment of machining models effort.

We share a third laboratory on the NIST main shop floor with the Fabrication Technology Division. This laboratory is used jointly for technology development and provision of services. The shared machines include: (1) a commercial high-accuracy, high-speed milling center with a 20,000 rpm, 18.7 kW (25 hp) spindle, and a capacity for 0.6 m/s maximum slide speeds and 0.2 m/s contouring speeds; and (2) a four-axis [x = 0.47 m, y = 0.35 m, z = 0.3 m, B = 360 degrees] high-speed grinder capable of high removal rates has a 26 kW (35 hp) drive motor and wheel spindle speeds of up to 14,000 rpm.

A fourth laboratory contains a three-axis machining center, an air-bearing traction drive single-axis motion control testbed, and a commercial turning center fully-instrumented with sensors (e.g., temperature, acoustic, and ultrasonic) and a touch-trigger probe.

Program Involvement

The mission and work of the division are realized through the following MEL programs:

- Advanced Optics Metrology
- Integrated Nano-to-Millimeter Manufacturing Technologies
- Mechanical Metrology
- Predictive Process Engineering
- Shop Floor as a National Measurement Institute
- Smart Machine Tools.

Intelligent Systems

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Developing the measurements and standards infrastructure needed for the application of intelligent systems

Mission and Responsibilities

The mission of the Intelligent Systems Division (ISD) is to develop the measurements and standards infrastructure needed for the application of intelligent systems by manufacturing industries. Intelligent systems integrate knowledge and feedback into a sensory-interactive, goal-directed control system that can make plans and generate effective purposeful action to achieve goals.

We conduct research to develop a basic understanding of the theoretical issues of intelligent systems, including architecture frameworks, sensory perception, and knowledge representation. We develop tools and engineering methodologies for building real-time controls for intelligent systems. We apply this research and these tools and methodologies to assist industry in the development, implementation, and testing of standards and performance measurement techniques to enable the effective, efficient, safe, and secure use and diffusion of intelligent systems. We also apply these capabilities to develop technologies and test evaluation procedures for autonomous systems in support of the mission needs of other government agencies.

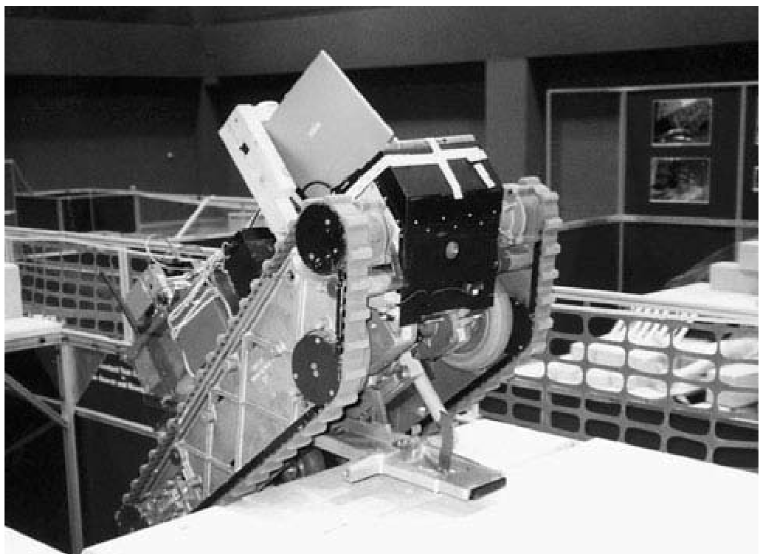
Resources

Staff

ISD has 34 permanent staff, of which 28 are engineers and computer scientists. The division augments the work of the permanent staff with the efforts of NIST associates including guest researchers, National Research Council (NRC) postdoctoral research associates (post-docs), and students. The ISD currently has four guest researchers, one NRC post-doc, and four students.

Equipment and Facilities

ISD uses a broad range of equipment and facilities to carry out its mission. Research equipment includes machine tools, industrial robots, coordinate measuring machines (CMMs), industrial process control hardware and software, a cable-based robotic crane, and a fleet of vehicles supporting research in autonomous mobility. A High Mobility Multi-Wheeled Vehicle (HMMWV) has been modified to allow autonomous operation and to house a variety of advanced sensors, such as high resolution LADAR, and stereo cameras. The HMMWV has a very high precision navigation system, which is used for data collection using the various sensors. Other vehicles include an Experimental Unmanned Vehicle (XUV) and an instrumented modified passenger car used for evaluating autonomous mobility technologies.



ISD's Reference Test Arenas for Urban Search and Rescue Robots are one example of our work to define and apply performance metrics for intelligent systems. The arenas help evaluate and further develop the capabilities of robots that assist human rescuers at disaster sites. The arenas are being replicated worldwide and used in numerous competitions.

ISD developed a series of Reference Test Arenas for Urban Search and Rescue Robots (USAR) to provide a series of realistic yet reproducible and isolatable challenges for USAR robots. These challenges test capabilities that USAR robots must have to be effective in assisting rescuers at disaster sites. The Reference Test Arenas are available to outside robotics research groups except when they are on loan to the annual Search and Rescue competitions. In FY 2003, the ISD is undertaking the development of two significant new facilities. The first is an Industrial Control System Cybersecurity Testbed to support work in Critical Infrastructure Protection. The second is a transformation of space in the NIST Shops to accommodate CMMs to be used for a Metrology Interoperability Testbed and machine tools for the Manufacturing Metrology Division-led Smart Machine Tool and Predictive Process Engineering programs. The development of the Shops testbeds is being undertaken as a joint effort of multiple MEL divisions, including the Fabrication Technology Division.

Program Involvement

ISD's activities include managing and participating in six MEL programs. We manage three programs: Intelligent Open Architecture Control (IOAC) of Manufacturing Systems, Intelligent Control of Mobility Systems (ICMS), and Critical Infrastructure Protection: Cybersecurity of Industrial Control. The IOAC program develops and validates interface standards and conformance tests to achieve interoperability of control systems for machines on the factory floor with design and planning systems, with factory data networks, and with each other. The ICMS program provides architectures and interface standards, performance test methods and data, and infrastructure technology needed by U. S. manufacturing industry and government agencies to develop and apply intelligent control technology to mobility systems. The CIP program work will increase the security of computer systems that control production and distribution in critical infrastructure industries, including electric power, oil and gas, water, chemicals, pharmaceuticals, metals and mining, pulp and paper and durable goods manufacturing. We also participate in three additional MEL programs: Predictive Process Engineering, Shop Floor as a National Measurement Institute, and Integrated Nano-to-Millimeter Manufacturing Technologies. ISD also conducts long-term foundational intelligent systems research in support of these programs. The goal of this research is to provide a clearly defined framework within which intelligent systems technologies can be readily evaluated, specified, and integrated by U.S. manufacturers. The main topics addressed are metrics, knowledge engineering, architectures and development tools, and learning. We are developing ways to measure performance, inter-compare research results, and define measurable objectives for intelligent systems applications We are working on tools and principles for building knowledge bases suitable for real-time perception and control in a way that promotes openness and interoperability. We are working with collaborators to develop infrastructural definitions and principles to guide the development of domain-specific architectures. We are also investigating the unique implications of introducing learning capabilities into intelligent systems, with respect to performance measures and architectures. As the demand grows for systems that are more adaptive, capable, and autonomous, these foundational measurement and infrastructural technologies will become increasingly critical to the design, implementation, and deployment of intelligent systems in a broad spectrum of applications.

Fabrication Technology

Mark Luce, Chief, 301 975 2159, mark.luce@nist.gov

Mission and Responsibilities

The mission of the Fabrication Technology Division (FTD) is to provide high-quality, reliable, and cost-effective fabrication and technical support services to all NIST staff. The FTD assists in the design and construction of instruments and devices needed to maintain the national and international standards of measurement and measurement services for which NIST has stewardship. We provide the engineering and manufacturing expertise and equipment needed to produce specialized parts and subassemblies for one-of-a-kind instruments conceived by NIST scientists and engineers. Our staff members perform a wide range of specialized precision fabrication and technical support services required to maintain the accuracy and performance of numerous measurement and testing instruments used by NIST scientists and engineers.

Providing high-quality, reliable, and cost-effective fabrication and technical support services to all NIST staff

Resources

FTD's specialized fabrication and technical support services include:

- optical fabrication
- glassblowing and glass fabrication
- CNC machining
- manual milling, turning, and grinding
- high-speed machining
- precision diamond turning
- sheet metal bending and forming
- mechanical engineering
- design, planning and estimating
- precision welding and soldering
- electrical discharge machining
- precision diamond turning
- mechanical inspection

In addition to the division's main shops area, we have five one-person "contact" shops conveniently located in buildings throughout the NIST campus to better serve our customers in other laboratories. We also maintain a complete inventory of ferrous and non-ferrous raw materials and operate the NIST metal storeroom facility.

The FTD is staffed by 41 full-time personnel, including engineers, instrument makers, machinists, technicians, and support staff. Staff members have master craftsmen level expertise in mechanical, glass, and optics fabrication processes, technologies, and equipment. This expertise allows us to perform precision machining, manufacturing, and assembly processes that create complex instruments and devices for NIST researchers.

Program Involvement

Many MEL research programs rely on the skill and experience of FTD staff members, not only for device design and construction but also for input into engineering and manufacturing process problems. FTD staff members have specialized experience in precision welding, high-speed machining, mechanical engineering design, in-process inspection, single point diamond turning, precision grinding, sheet metal fabrication, production planning and estimating, and thin-film deposition processes. FTD's staff communicates with its customers within MEL and NIST in various ways, including one-on-one consultation services on part specifications and manufacturing processes. These collaborative efforts are instrumental in maintaining a state-of-the-art support service for NIST, while at the same time helping NIST researchers prove-out new metrology-based systems.

Manufacturing Systems Integration

Steve Ray, Chief, 301 975 3524, steven.ray@nist.gov

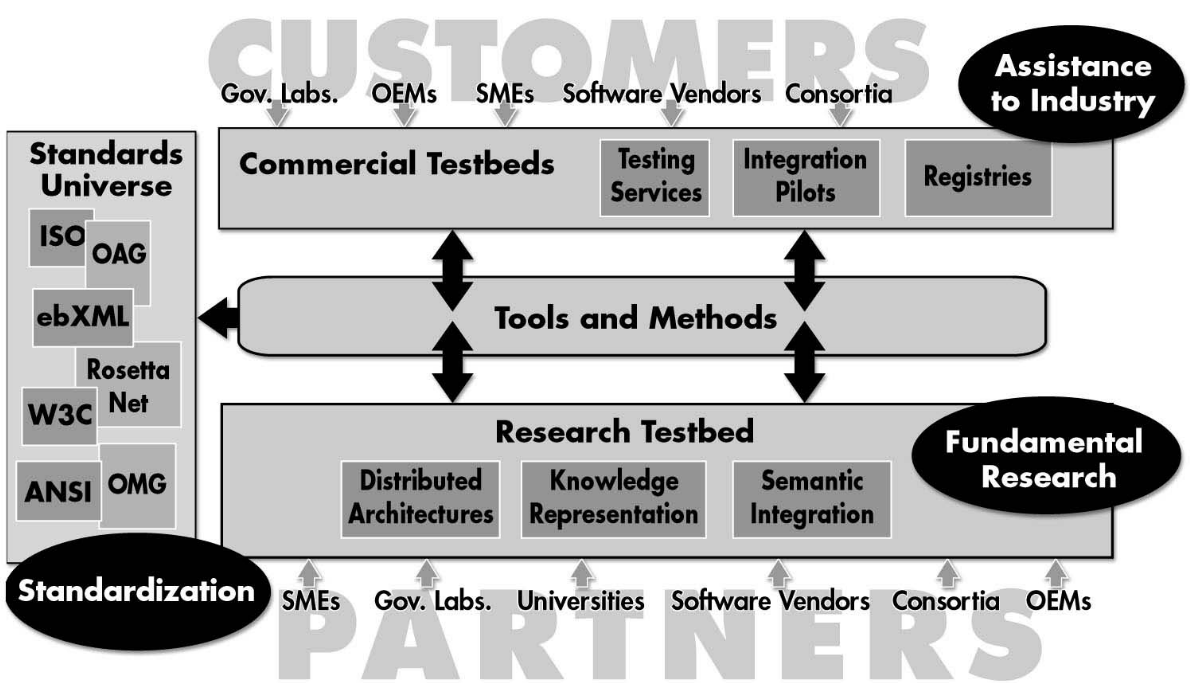
Mission and Responsibilities

The mission of the Manufacturing Systems Integration Division (MSID) is to promote economic growth by working with industry to develop and apply measurements and standards that advance the use of information-based manufacturing technology.

MSID responds to industry priorities for interoperability solutions by defining technically sound, neutral integration standards in cooperation with industrial partners. The division also contributes to the development of mechanisms for assessing conformance and interoperability of software implementations using these standards to ensure that the standards solve the targeted problems. Our fundamental research, in collaboration with industry consortia, small and medium-sized enterprises (SMEs), original equipment manufacturers (OEMs), universities, software vendors, and government laboratories further distinguish our overall contributions to a fully integrated, interoperable enterprise. See Figure 1.

Promoting economic growth by working with industry to develop and apply measurements and standards that advance the use of information-based manufacturing technology

Figure 1: MSID's Enterprise Integration Support



As the manufacturing community strives to harness and exploit the capabilities of information technology (IT), the MSID responds by drawing on advances in manufacturing systems integration theory to help define and promulgate timely, technically sound, open specifications for the interoperation of manufacturing systems.

Developing viable IT standards for manufacturing is particularly challenging given the rapid pace of change in technology. Interoperability between systems is becoming one of the principal barriers to achieving the decreased time-to-market demanded by today's competitive environment, and it is only through the adoption of new approaches that the standards community will be able to respond. Figure 2 shows the predicted evolution from traditional data-exchange standards to a more powerful and agile systems-integration technology. This evolution includes the use of computer-readable exchange standards; increasingly rigorous standards expressed using formal languages; and advanced technologies to support dynamic, "self-integration."

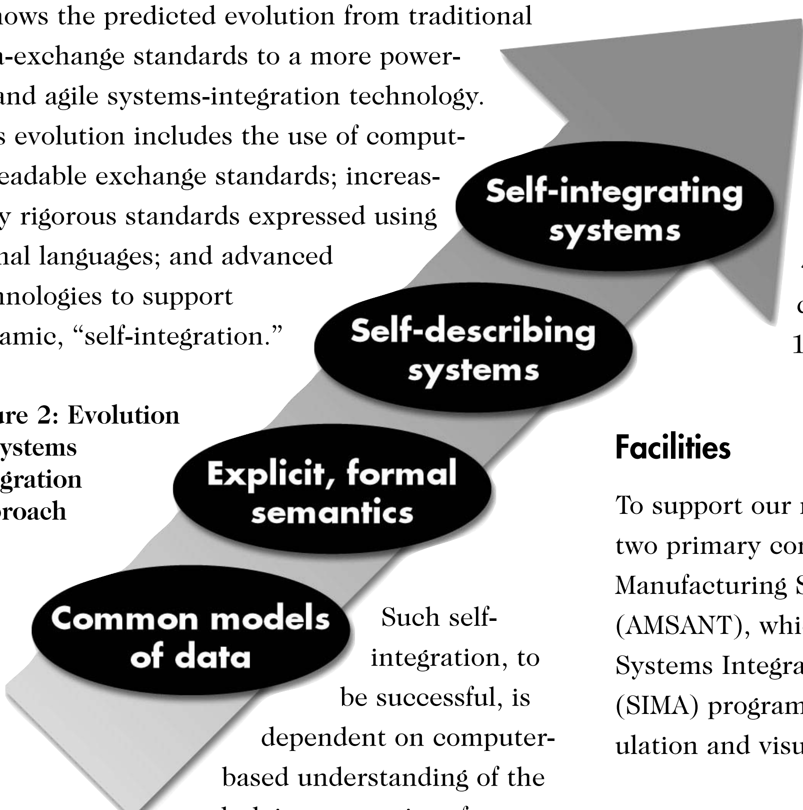


Figure 2: Evolution of Systems Integration Approach

Such self-integration, to be successful, is dependent on computer-based understanding of the underlying semantics of information being exchanged. As shown in Figure 1, one aspect of our fundamental research is in the direction of developing an understanding of, and potential metrics for, semantic integration. This work involves the development of standards, test methods, and pilot implementations built upon these new techniques.

Resources

Staff

The MSID staff consists of an unusually high ratio of guest researchers to permanent federal employees – roughly 50/50. This mix exists because we strongly emphasize the value of augmenting the capabilities of our permanent staff with NIST associates. The academic credentials of the staff are mostly in the computer science or engineering fields, with approximately 40 percent in computer science and 45 percent in electrical, industrial, manufacturing, or mechanical engineering. Other professional disciplines represented include operations research and mathematics. Across all of MSID's current staff, 41 percent have obtained doctoral degrees, 39 percent master's, and 14 percent bachelor's degrees.

Facilities

To support our many technical activities, MSID has two primary computer laboratories: the Advanced Manufacturing Systems and Networking Testbed (AMSANT), which is supported and operated by the Systems Integration for Manufacturing Applications (SIMA) program, and an integration testbed for simulation and visualization activities.

The AMSANT provides a distributed, multi-node facility to enable collaborative development and testing of manufacturing systems integration specifications intended to support distributed and virtual manufacturing enterprises. The testbed infrastructure supports the research by combining advanced computing and communications technology with digital library services.

Working with manufacturing software vendors, MSID has also established the integration testbed that contains manufacturing and engineering software applications for simulation and visualization. Such applications would normally be very costly for a developer or integrator to acquire. MSID staff members have hands-on experience working with all of these packages, and we also participate in the standards development organizations that define the standard interfaces between these applications.

Program Involvement

MSID is wholly involved in and focuses many of its resources in the following programs: Product Engineering, Manufacturing Enterprise Integration, and Manufacturing Simulation and Visualization. We are also substantially involved in two other programs: Predictive Process Engineering and Integrated Nano-to-Millimeter Manufacturing Technologies. MSID plays smaller roles in the Shop Floor as a National Measurement Institute (NMI), Intelligent Control of Mobility Systems, Intelligent Open Architecture Control for Manufacturing Systems, and Large-Scale Metrology programs.

Most of MSID's current long-term programmatic work falls within the NIST strategic focus area of Information and Knowledge Management. Additionally, MSID has begun to invest some of its resources into two other NIST focus areas: Health Care and Homeland Security. Within the infrastructure of the health care supply or "value" chain, MSID is working with others at NIST to apply and integrate electronic commerce technology. We are also extending our work in distributed simulation to potential applications to homeland security and emergency preparedness.

Underlying many of these technical programs is the division's management of the NIST-wide SIMA Program, an inter-laboratory effort applying IT solutions to manufacturing systems integration problems in conjunction with the multi-agency Federal Networking and Information Technology Research and Development Initiative. Started in 1994, the SIMA Program strives for reduced time-to-market for highly engineered products by improving the productivity of engineering and manufacturing through the widespread adoption of information standards.

SIMA contributes to more than a dozen research programs and projects throughout NIST. These efforts address manufacturing integration issues in two technology areas: interface standards and information access. The SIMA Program seeks to improve the overall integration of manufacturing systems by facilitating the development and testing of information exchange protocol standards, and by sponsoring work to open a wealth of scientific and engineering information in NIST databases to manufacturers, researchers, and academia. The results of these efforts will allow manufacturing industries to communicate product and process data among various manufacturing activities such as product and process design, analysis, planning, scheduling, production, and quality control.

Programs

Programs @ a Glance

ADVANCED OPTICS METROLOGY

Program Manager:	Clayton Teague – Acting
Phone:	301 975 6600
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FTEs:	3.0
Program Funding:	$556 K

Program Goal

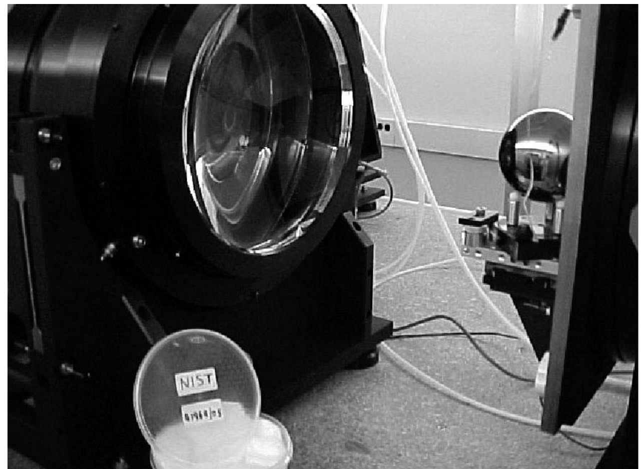
Develop and provide NIST measurement services for flatness, radius of curvature, and optical figure with Systeme Internationale d'Unites (SI) traceable expanded uncertainties of 0.25 nm rms or better over apertures up to 300mm for the optics, microelectronics, and data storage industries.

Problem

Current measurement technology is increasingly inadequate to meet the geometrical tolerance requirements of ultra-precise optics with aspheric surfaces, such as optical elements and semiconductor substrates for fabricating next-generation micro-electronics and optoelectronics. Even modeling of the optical performance of critical elements is limited by the inability to measure parameters such as radii of curvature. There are currently no standard test methods or NIST measurement services to meet these needs.

Approach

We are implementing a new measurement capability, known as the NIST X-ray accurate optics CALIBration InterferometeR (XCALIBIR). XCALIBIR's ultra-high resolution and our interferometer capable of operating at infrared wavelengths provide a combined capability to measure optical figure as well as subsurface damage and thickness variations of semiconductor wafers.



Radius-of-Curvature measurement of an ultra-precision silicon sphere

Customers and Collaborators

- ASML/Tinsley
- Kansas State University
- Komatsu
- MEMC
- Microelectronics, data storage, and optics defense system supplier industries
- NASA
- Optimax Systems
- Taylor Hobson, Ltd.
- University of Northern Carolina
- Virginia Semiconductor
- Wavefront Science

CRITICAL INFRASTRUCTURE PROTECTION

Program Manager:	Fred Proctor
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FTEs:	1.5
Program Funding:	$433 K

Power plants such as this form the nation's critical infrastructure. Securing them against cyberattack is a top priority.

Program Goal

Increase the security of computer systems that control production and distribution in critical infrastructure industries, including electric power, oil and gas, water, chemicals, pharmaceuticals, metals and mining, pulp and paper, and durable goods manufacturing by (1) defining and applying standard information security requirements, (2) developing information security best practice guidelines and conducting outreach activities, and (3) developing laboratory and field test methods for information security products and approaches applied to the process control sector.

Problem

The computer systems that control industrial production and distribution have been designed first and foremost to meet performance, reliability, safety, and flexibility requirements. Yet these systems increasingly incorporate connectivity and remote access capabilities. Industry has begun to appreciate that increased connectivity and openness are introducing serious vulnerabilities into operational systems. One critical problem of immediate concern is the absence of methods to specify and verify the security characteristics of control system components and networks. These are problems that the Common Criteria for Information Technology (IT) Security Evaluation, developed by NIST and the National Security Agency (NSA), are intended to address.

Approach

To develop IT security requirements for industrial control systems, NIST is working with industry through its leadership of the Process Control Security Requirements Forum (PCSRF). Through the PCSRF, the following steps are being taken to develop process control information security requirements:

- analyze currently available computer control system architectures, including analysis of threats and vulnerabilities;
- develop information security requirements, in language and format understandable to the process control users and vendors; and
- translate Information Security Requirements into Common Criteria Protection Profiles that can be used to enable testing and evaluation of covered computer control system products/systems by accredited IT security testing laboratories.

Customers and Collaborators

- American Gas Association
- American Water Association
- Dow Chemical
- Dupont Chemical
- Gas Technology Institute
- Georgia-Pacific
- Instrumentation Society of America
- KEMA Consulting
- Maximum Control Technology, Inc.
- U.S. Department of Energy

ENGINEERING METROLOGY

Program Manager:	Ted Doiron
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FTEs:	8.2
Program Funding:	$1.3 M

Silicon sphere fixtured on M48 CMM

Program Goal

Provide world-class engineering metrology resources for our customers to promote the health and growth of U.S. discrete-parts manufacturing by delivering significantly improved, state-of-art uncertainty levels for industry-critical measurement services; reducing calibration turn-around time and increasing percentage of calibrations completed on time in key calibration areas; and developing new measurement techniques to meet emerging industry needs.

Problem

The Engineering Metrology Group has the largest dimensional measurement customer base of any NMI in the world, perhaps by an order of magnitude. This program allows US industry unparalleled access to state-of-the-art measurements by providing very high accuracy and high throughput services. Improved service to our customers will enhance U.S. ability to compete in world markets, and new competencies will provide opportunities for U.S. industry to grow and compete.

Approach

This program takes a broad approach to improving all aspects of Engineering Metrology services to industry based on delivery of high-quality measurement services with increased efficiency, coupled with research into new measuring methods. For the small hole area, we plan to expand our capabilities for industry-needed measurements of small, high-relief structures (such as 125 mm holes), with nano-force probing. In the grid plate area, we will demonstrate world-class (sub-100 nm uncertainty) 2-D video-based CMM measurements on M48 CMM and will provide materials (grid SRM) needed to improve 2-D metrology in semiconductor manufacture. The Dilatometer project will provide industry with the needed thermal expansion coefficients of characteristic, key artifacts, measured with new system for high-accuracy dilatometry. We will develop systems for state-of-art cylindrical form measurement.This year, we will begin final implementation of the new systems for gage block and sphere calibration needed to improve calibration efficiency by reducing number of needed master artifacts. Over 200 companies rely on us for calibrations, and a much wider audience is interested in the information and techniques that we develop. Our customers are important and we address their needs through technical meetings, information on our web site, training courses in dimensional metrology, collaborating with graduate students and guest researchers, and CRADAs with private industry. We calibrate over 5000 artifacts each year, providing a traceable link to the definition of the meter for more than 160 organizations in 40 states.

Customers and Collaborators

- Aerospace Industry
- Automotive Industry
- Heavy equipment Industry
- Telecommunication industry
- Measuring tool and machine tool industries

INTEGRATED NANO-TO-MILLIMETER MANUFACTURING TECHNOLOGIES

Program Manager:	Kevin W. Lyons
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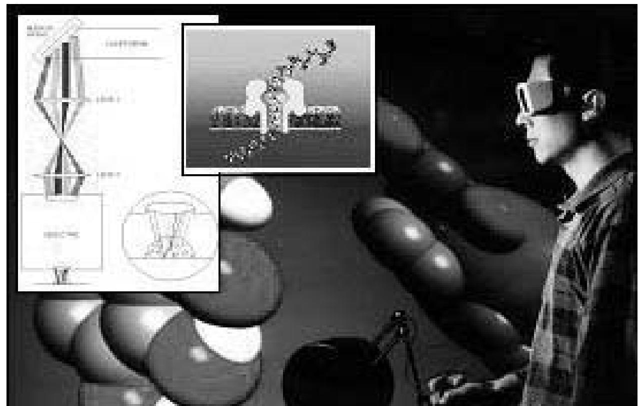
FTEs:	9.25
Program Funding:	$883 K



Program will develop models, architectures, and methods that support improved human-computer interfaces for controlling complex instruments.

Program Goal

Address the anticipated needs of the emerging U.S. nanotechnology industry; develop and deliver models, architectures, and methods for process measurement and control systems that enable manufacturing across nm-to-mm scales.

Problem

Major industrial and scientific trends that emerged during the 1990s will influence not only how manufacturing will be done over the next decade, but also what is manufactured. The size of many manufactured goods continues to decrease, resulting in ultra-miniature electronic devices and new hybrid technologies. For example, microelectromechanical systems (MEMS) devices integrate physical, chemical, and even biological processes in micro- and millimeter-scale technology packages. MEMS devices now are used in many sectors: information technology (IT), medicine and health, aerospace, environment, and energy to name a few. On the horizon is the development of nanomanufacturing technologies that will support tailor-made products having functionally critical nanometer scale dimensions produced using massively parallel systems or self-assembly. There is a need to develop advanced models, new architectures, and innovative methods for process measurement systems that will serve as enablers for the US nanotechnology industry and as a foundation for standards that support this emerging market.

Approach

The research effort is comprised of three thrusts; 1) atomic-scale manufacturing, 2) molecular-scale manipulation and assembly, and 3) micro-to-millimeter scale manufacturing technologies, each focused on a specific application area and problem set. Each of the thrust areas will address unique aspects regarding the development of models, architectures, and methods. Throughout all phases of the program, the knowledge learned in each of the thrust areas will be shared with the others to maximize the outcomes of the program.

Customers and Collaborators

- SEMATECH
- Johns Hopkins University Applied Physics Laboratory
- Massachusetts Institute of Technology
- NASA Goddard Space Flight Center
- Penn State University
- Purdue University
- Texas Nanotechnology Initiative
- University of Arkansas
- University of California– Los Angeles
- University of Maryland, College Park
- University of New Mexico
- Washington State University – Virtual Assembly Technologies Consortium
- Wichita State University

INTELLIGENT CONTROL OF MOBILITY SYSTEMS

Program Manager:	Maris Juberts
Phone:	301 975 3424
Email:	juberts@cme.nist.gov
FTEs:	14.0
Program Funding:	$4.3 M

Program Goal

Provide architectures and interface standards, performance test methods and data, and infrastructure technology needed by U.S. manufacturing industries and government agencies in developing and applying intelligent control technology to mobility systems to reduce cost, improve safety, and save lives.

Problem

Customers have a variety of measurement and standards needs. To develop and use intelligent mobile systems, industry and government agencies need architectures and interface standards to ensure interoperability, real-time sensing technologies for measurement and control, and metrics for evaluating the performance of components and systems.

Approach

The Intelligent Control of Mobility Systems Program will provide industry with standards, performance metrics, and infrastructure technology to broaden the use of advanced perception and autonomous navigation techniques; provide defense agencies with the control system architectures, advanced sensor systems, research services and standards to achieve the use of unmanned ground vehicles in the battlefield; provide the evaluation and measurement methods, testing procedures, standard reference data needed to support the deployment of advanced technology in transportation and industrial safety systems, and in future combat systems.

The program will use the NIST Real-time Control system (RCS) architecture as an example of an open system architecture for building complex autonomous robotic systems for other government agency programs and funds and then invest direct appropriations to transfer relevant advanced robotics technology to industrial applications.

Customers and Collaborators

- Advanced Scientific Concepts
- Army Research Lab
- Boeing
- Carnegie Mellon University (CMU)
- Coherent Technologies
- Daimler Chrysler/Dornier
- Defense Advanced Research Projects Agency (DARPA)
- Department of Transportation-National Highway Traffic Safety Administration (DOT-NHTSA)
- Drexel University
- GDRS
- General Dynamics
- Jet Propulsion Lab
- John Deere Co.
- Lockheed Martin
- Raytheon
- Sandia National Lab
- Science Applications International Corporation (SAIC)
- The Ohio State University
- Universitat der Bundeswehr/Munich
- University of Maryland

Intelligent Open Architecture Control

Program Manager:	Fred Proctor
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FTEs:	10
Program Funding:	$1.5 M

Program Goal

Develop and validate key interface standards, and conformance tests for those standards, to achieve interoperability among control systems for machines on the factory floor and between these systems and design and planning systems, as well as factory data networks.

Problem

Over the past two decades, information technology has dramatically increased the intelligence of the upper levels of manufacturing systems. In the next 20 years, this intelligence will reach down to the factory floor as individual machines become much smarter, more easily integrated, and able to communicate more broadly, predict results and avoid or diagnose mistakes, use extensive in-process gaging, and use scientific models to optimize productivity.

These trends, echoed in the Integrated Manufacturing Technology Roadmap (IMTR, now known as the Integrated Manufacturing Technology Initiative [IMTI]), have great potential to decrease time and cost to market, improve quality, and increase productivity. However, they require a seamless flow of information and total integration throughout the enterprise, and today, in the words of one industry workshop attendee, “all the links are broken.”

The lack of interoperability costs U.S. industry billions of dollars. A typical robot installation costs 3 to 5 times the actual cost of the robot (1999 Robotics Industry Forum). The aerospace industry also cites similar data: $10 million of capital equipment can take as much as 100 person years to integrate. (Boeing data)

Approach

The program seeks to realize interoperability by facilitating and participating in industry efforts to standardize open architecture control—a common architecture of system components and interfaces—which is the key to connecting systems and realizing the benefits of increased intelligence in manufacturing. Program staff hold workshops, in collaboration with industry and government agencies, to identify the most pressing interoperability problems; facilitate and participate in industry efforts to develop suitable architectures as a basis for interface specifications; establish testbeds with real manufacturing equipment to implement and test candidate specifications; and, in cases where conformance tests are needed to ensure interoperability, work with industry to develop them.

The program is intended to accelerate the implementation and commercial availability of controllers with advanced capabilities, and to reduce controller life cycle costs due to easier integration of controller components and increased competition among controller component vendors. This benefits U.S. controller vendors and users differentially by helping them to gain a competitive advantage in implementing and applying advanced capabilities at lower costs.

Customers and Collaborators

- American Welding Society
- Automotive Industry Action Group
- Instrumentation Society of America
- Metrology Automation Association
- Open DeviceNet Vendors Association
- Open Modular Architecture Controller Users Group
- Robotic Industries Association

LARGE SCALE METROLOGY

Program Manager:	Charles J Fronczek Jr.
Phone:	301 975 4079
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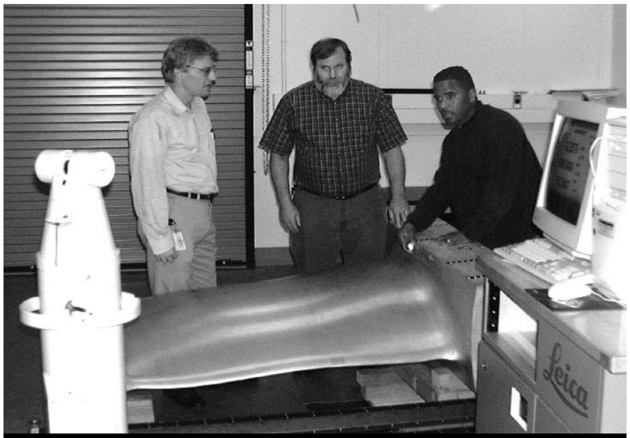
FTEs:	1.9
Program Funding:	$501 K



Large Scale Coordinate Metrology Group members discuss methods to measure complex geometries.

Program Goal

Provide U.S. large-scale-manufacturing metrologists with the tools—standards, artifacts, and methodologies—for characterizing the performance of coordinate measuring systems.

Problem

In general, traditional large scale coordinate measuring machines (CMMs) collect sparse, discrete-point coordinate data; the output of these systems is often used to characterize the size, shape, and orientation of simple geometric elements. The latest large scale coordinate measuring systems (CMSs) collect dense clouds of data, with the intent of characterizing large, free-form complex surfaces. Users need to know the uncertainty associated with the measurements made by these systems both in support of manufacturing and for intercomparison of like instruments. Conventional artifacts are inadequate for evaluating the performance of these systems. Moreover, the software used to fit raw measurements to geometric representations of a workpiece tends to compound the uncertainty problem. Users and vendors seek objective analytical methods and tools as well as a neutral test service to assess the uncertainty of the measurement results.

Users (Boeing, the Propulsor Group of the Naval Surface Warfare Center (NSWC), Large Millimeter Telescope group (LMT)) and equipment manufacturers (Dimensional Photonics, Automated Precison Inc., Imetric SA) have expressed orally and in writing both their need for NIST services and their great concern over the critical lack of a research base in these areas.

Approach

The problem is being addressed through standards development, methodology research, artifact development, and software testing.

Customers and Collaborators

- Aerospace Industry
- Automated Precison Inc.
- Boeing
- Caterpillar
- Dimensional Photonics
- Imetric SA
- Large Equipment Manufacturers
- Large Millimeter Telescope group
- Propulsor Group of the NSWC
- Shipbuilding Industry

MANUFACTURING ENTERPRISE INTEGRATION

Program Manager:	Al Jones
Phone:	301 975 3554
Email:	albert.jones@nist.gov
FTEs:	10
Program Funding:	$1.6 M

Program Goal

Demonstrate a cost reduction for Business-to-Business (B2B) software integration using new types of semantics-based measurements, standards, and infrastructural technologies that automate the process of integration

Problem

The Internet is a critical part of the business strategy of most manufacturing enterprises. Internet communication standards govern the exchange of bits and bytes from one computer to another. Thus, the Internet enables manufacturers to link up with partners, suppliers, and customers anywhere in the world.

The Internet, however, is not enough. To turn business possibilities into realities, users require the integration of a myriad of enterprise-level software applications. Several market analysts, including Gartner and D.H. Brown, project that the market for these applications will reach $100 billion by the year 2005. They also estimate that integration costs range from two to five times the software cost.

Approach

We initiated a new research effort, called AMIS (Automated Methods for Integrating Systems) to investigate the automation of software integration. We will use emerging enterprise-modeling techniques to capture interaction ontologies – the business entities and functions involved in the integration task. We will use software-modeling techniques to capture implicit ontologies – the objects and information a component deals with and the functions it performs. We will convert the models to forms suitable for processing by artificial intelligence techniques. We will use semantic-analysis techniques to develop mappings between the implicit ontologies and the interaction ontology. And, we will use knowledge bases, expert-systems techniques and code- generation techniques to generate runtime tools that implement the semantic mappings by converting messages between components.

We continued development of the B2B Interoperability Testbed, which provides an infrastructure for interactions among manufacturers, standards organizations, and software vendors. Manufacturing companies provide integration scenarios. Standards organizations provide specifications that cover all aspects of interoperability. Vendors use the tesbed, scenarios, and specifications to assess, analyze, measure, and demonstrate on-demand integration of their software products. We give guidance for coordination of interactions, develop conformance test, provide test data, and conduct interoperability tests.

Customers and Collaborators

- Automotive Industry Action Group
- Boeing
- Lockheed Martin
- Managing B2B
- Open Applications Group
- RosettaNet
- University of Maryland, Baltimore County
- University of South Carolina

MANUFACTURING SIMULATION & VISUALIZATION

Program Manager:	Charles McLean
Phone:	301 975 3511
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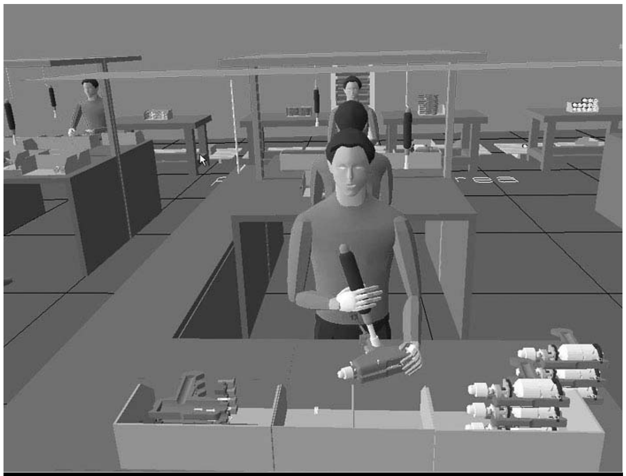
FTEs:	8.5
Program Funding:	$787 K

Program Goal

Establish an initial set of standard interfaces and testing capabilities to enable distributed manufacturing simulation and advance the interoperability of manufacturing simulation systems and related software applications.

Problem

Simulation technology holds tremendous promise for reducing costs, improving quality, and shortening the time-to-market for manufactured goods. However, this technology remains largely underutilized by industry today. A number of factors inhibit the deployment of simulation technology. For example, no industrial standards organization is focusing on the development of manufacturing simulation standards. Interface standards could reduce the expenses associated with technology acquisition and deployment, minimize model development time and costs, and provide new types of simulation functionality that are not available today. NIST expects to play a major role in helping industry implement simulation and virtual manufacturing technology through the development of interface standards.



Simulation of a Power Tool Assembly Line

Approach

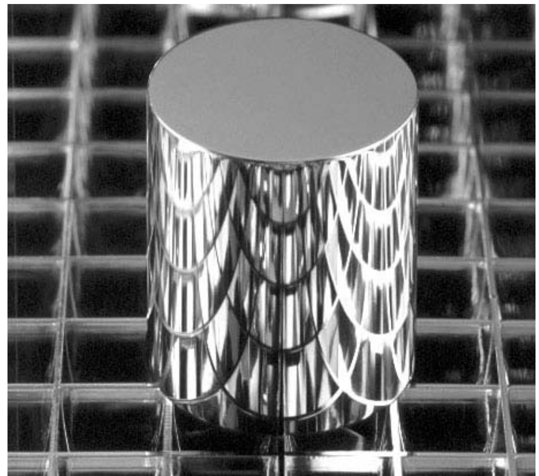
We are working with industry, academia, and other government agencies to identify interoperability requirements for simulation. Our current efforts are focused on the specification of data models and interfaces for integrating manufacturing simulation systems with other applications in a machine shop environment. A prototype generic machine shop simulator is under development for use in evaluating the feasibility of proposed interface standards. The results of this work will be made available to a wide variety of machine shops through the Software Engineering Institute's Technology Insertion Development and Evaluation (TIDE) Program. NIST staff are promoting the results of this project as candidate neutral interfaces within manufacturing industries, and the simulation software and standards communities.

Customers and Collaborators

- Aerospace Industry
- Automotive Industry
- Industrial Equipment Industry
- Machine Shops
- Mechanical Products Manufacturing Industry
- Semiconductor Industry
- Simulation Software Vendors
- Standards Development Community

MECHANICAL METROLOGY

Program Manager:	David J. Evans
Phone:	301 975 6637
Email:	dje@nist.gov
FTEs:	10
Program Funding:	$2,415 K



The U.S. International Prototype Kilogram maintained by the Mechanical Metrology Program

Program Goal

Provide full institutional support to realize, disseminate, maintain, standardize, and improve the realization of the mechanical quantities of acoustics, force, mass, and vibration.

Problem

To achieve efficiency in commerce and ready access to foreign markets, U.S. industry needs measurements of mechanical quantities that are traceable to the appropriate national and international standards. Industry therefore requires internationally recognized calibration services that support mechanical quantities, as well as a means of maintaining international equivalence of measurement services, recognition of calibration certificates and measurement capabilities, and acceptance of test and calibration methodologies.

Approach

NIST, the internationally recognized National Measurement Institute of the U.S., represents U.S. interests on the International Committee of Weights and Measures (CIPM) and its consultative committees and on Regional Metrology Organizations in the Americas.

This program realizes, maintains, disseminates, and improves the national physical standards for mechanical quantities. The program also establishes the equivalence and standardizes the realization of these quantities through participation in international and regional metrology organizations and in international and national documentary standards development organizations.

Customers and Collaborators

- Aerospace Industry
- Automotive Industry
- Construction Industry
- Nuclear Power Industry
- Pharmaceutical Industry
- Instrument Manufacturers
- University Research Labs
- State Weights and Measures Labs
- Federal Agencies - Dept. of Agriculture, Dept. of Commerce, Dept. of Defense, Dept. of Energy, Dept. of Labor, Dept. of Veterans Affairs, Dept. of Justice, and the Food & Drug Administration

NANOMETER-SCALE METROLOGY

Program Manager:	Michael T. Postek
Phone:	301 975 2299
Email:	postek@nist.gov
FTEs:	11.9
Program Funding:	$1,866 K

Program Goal

Provide to the U. S. microelectronics industry, directly or indirectly, reference measurements, reference standards and infrastructural metrology identified as necessary to help the industry to continue the historical rate of dimensional reduction and to subsequently realize its production goal of sub-100 nm devices by 2005 and beyond.

Problem

The semiconductor, flat panel display, and high-density memory manufacturing industries need measurement methods and artifacts whose dimensions are known with nanometer-scale accuracy. Of these industries, the strongest push and clearest direction is provided by the ever-demanding needs of the semiconductor industry. Nanometrology developed for semiconductor applications can be rapidly leveraged by other industrial sectors as the applications develop.

Approach

Length measurements in the nanometer scale regime are accomplished by a number of methodologies including tunneling, atomic-force, electron, and visible and ultraviolet light microscopes. Computer modeling and standards development are also integral parts of the measurement process. Research and development (R&D) focuses on potentially "disruptive technologies," such as high-pressure/environmental microscopy and nano-tip emitters for scanning electron microscopy. R&D work on the potential of developing and incorporating intrinsic standards using the atomic lattice, fabrication of sub-50 nm calibration structures using unique lithographic techniques and instrument performance characterization is also ongoing.

Solving the advanced metrology needs of the semiconductor industry allows rapid application of nanometer-scale technology into other industrial sectors.

Customers and Collaborators

- Applied Materials
- Argonne National Labs
- Dupont Photomasks
- E. Fjeld Co.
- EDAX, Inc.
- Hewlett-Packard Co.
- Hitachi High Technology
- International SEMATECH
- KLA
- NRL
- Photronics, Inc.
- Schlumberger
- SEM Tech Solutions
- SEMI
- Semiconductor Research Corporation
- Spectel Research
- UNC Charlotte
- University of Akron
- University of Maryland
- University of South Florida
- University of Tennessee/Oak Ridge Natl. Labs.
- VEECO/FEI Co.
- VLSI Standards
- XEI Scientific

PREDICTIVE PROCESS ENGINEERING

Program Manager:	Kevin Jurrens
Phone:	301 975 5486
Email:	kevin.jurrens@nist.gov
FTEs:	9.5
Program Funding:	$1.7 M

Program Goal

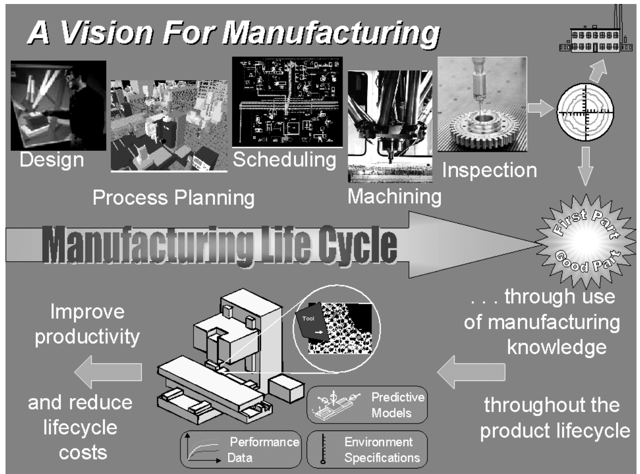
Establish an integration framework for sharing predictive knowledge about machining processes and resources with engineering and control systems using a standard semantic-based process representation and validated physics-based models for milling and turning.

Problem

Manufacturing process parameters, such as machining speeds, feed rates, and tool selection, are typically chosen by costly, trial-and-error prototyping, resulting in solutions that are often sub-optimal. There are two principal barriers to reductions in manufacturing process inefficiencies: lack of access to validated, physics-based models of the manufacturing processes when key engineering decisions are made; and lack of simple mechanisms to enable exchange of process information among manufacturing systems.

Approach

The program will build a foundation for "first part correct" manufacturing based upon a science-based understanding of material removal processes, advanced process metrology methods, validated analytical models to predict process performance and optimize manufacturing decisions, and rigorously-defined representations for manufacturing process information. Program results will be integrated and demonstrated through a prototype integration framework for sharing predictive process knowledge.



Program results will demonstrate an integrated, model-based approach for making predictive knowledge about manufacturing processes accessible when key decisions are made.

Customers and Collaborators

- Alcoa
- Boeing
- Caterpillar
- Ford
- General Motors
- Knowledge Based Systems Inc. (KBSI)
- Naval Surface Warfare Center
- Oak Ridge National Laboratory
- Third Wave Systems
- U.S. Army Picatinny Arsenal
- University of Florida
- University of Maryland
- University of North Carolina at Charlotte

PRODUCT ENGINEERING

Program Manager:	Ram D. Sriram
Phone:	301 975 3507
Email:	sriram@nist.gov
FTEs:	9
Program Funding:	$1077 K

Program Goal

Establish a semantically based, validated, product representation scheme as a standard that supports the seamless interoperability among current and next-generation computer-aided design (CAD) systems and between CAD and other systems that generate or use product data to help the manufacturing industry achieve a 10% reduction in interoperability costs and a tenfold improvement in design exploration capability.

Problem

A major problem with the emergence of various heterogeneous CAD systems is the lack of interoperability among them. Interoperability problems cost the U.S. automotive supply chain at least $1 billion per year, according to a recent RTI International study; other industries are in similar predicaments. This problem has significant implications for the costs at all design stages and overall product cost, because decisions made during the design stage determine 70 percent of a product's cost over its life.

Approach

This program's activities and efforts range from specification and standards development to technology development and prototype implementation. The program is intended to provide the foundation to support the creation of next-generation product development tools, thereby increasing the efficiency, effectiveness, capability, and productivity of U. S. industry.

The primary objectives are to (1) extend the capabilities of ISO 10303 (Standard for the Exchange of Product Model Data, or STEP) by the provision of new resources allowing the capture and exchange of parametric, constraint-based and feature-based models; (2) develop standard representation and protocols for exchanging assembly and system-level tolerance information to enable semantic interoperability between design and manufacturing software systems, including immersive environments; (3) generate an information model - based on ISO STEP - for representing heterogeneous material data to improve data transfer capabilities from CAD to rapid prototyping/layered manufacturing (RP/LM) systems; (4) develop and publish an information modeling framework based on a semantically rich core product representation for the support of close integration of design and analysis activities throughout the design lifecycle of an artifact; and (5) create a broad foundation for the development of next-generation product development tools, which will consist of a core product model for the representation and exchange of product knowledge, including design rationale, and implement a prototype software tool suite, with a general approach using formal semantics.

Customers and Collaborators

- Advanced Technology Institute
- American Society of Mechanical Engineers 14.5
- Black and Decker
- Carco Electronics
- Carnegie Mellon University
- George Washington University
- IBM
- ISO
- KAIST (Korea)
- Nihon Unisys (Japan)
- Object Management Group (OMG)
- Stanford University
- Syracuse University
- Thar Designs
- University of Maryland
- University of Michigan
- University of Missouri-Rolla
- University of Texas-Austin
- University of Wisconsin-Madison
- Washington State University

SHOP FLOOR AS AN NMI

Program Manager:	Steve Phillips
Phone:	301 975 3565
Email:	steven.phillips@nist.gov
FTEs:	2.5
Program Funding:	$579 K

Program Goal

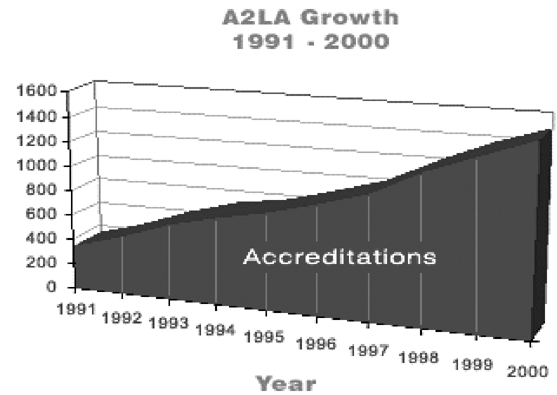
Enable the U.S. industrial dimensional metrology community to assert measurement traceability to the Systeme Internationale d'Unites (SI) unit of length.

Problem

The globalization of the economy is strongly driving national and international quality assurance and accreditation programs such as ISO 9000 and ISO 17025, as a means of assuring quality control of components fabricated throughout the world. Most of these standardization and accreditation programs require traceable measurements and hence measurement uncertainty statements. Consequently, U.S. industry is under new pressures to comply with these requirements while being stymied by a poor understanding and incomplete development of measurement uncertainty and traceability issues.

Approach

This program seeks to provide a set of documentary standards, guidelines, and reports to develop and elucidate metrological traceability and measurement uncertainty for dimensional metrology. Additionally, the program seeks to address specific problematic sources of uncertainty and conduct research to characterize these sources in a manner compliant with national and international standards.



The rapid rise in laboratory accreditation programs over the last decade.

Customers and Collaborators

- Boeing
- Caterpillar
- Hutchinson Technology
- Mitutoyo America
- Physikalisch-Technische Bundesanstalt (Germany)
- U.S. Air Force

Smart Machine Tools

Program Manager:	Johannes A. Soons
Phone:	301 975 6474
Email:	soons@nist.gov
FTEs:	5
Program Funding:	$866 K

Application of a grid encoder to test and improve the contouring performance of a machining center.

Program Goal

Develop metrology and standards to enable a machining or turning center to provide intelligent feedback on the health of its components and the tolerances it realizes, while autonomously invoking maintenance or tuning operations needed to continue producing the first and every part to specifications.

Problem

Machine tools are the key tools for discrete part and tooling fabrication. Improvements in these machines have a highly leveraged impact through gains in productivity and product quality. Users of machine tools need to deal with ever-more complex parts, closer tolerances, shorter lead-times, and smaller batch sizes. To succeed they need accurate and reliable machines whose performance is known and "guaranteed" for a wide variety of tasks and conditions. However, machine tools are subject to many error sources that change over time, are difficult to assess, and have effects that are task specific and difficult to predict. Thus users have to resort to costly part inspection and dedicated tuning to achieve requested tolerances. Moreover, they lack capabilities to harmonize part design with machine tolerance capabilities.

Approach

The program is working with industry, academia, and Other Agencies to develop the enabling metrology, smart sensor systems, and standards to characterize, monitor, and improve machine accuracy and reliability. The emphasis is on agile environments.The research addresses 1) parameters, test methods, and standards to evaluate machine performance; 2) standardized formats and infrastructure for the exchange of performance data; 3) methods to translate performance parameters into expected tolerances of machined parts; 4) methods and sensor applications to monitor and improve machine accuracy; 5) methods and sensor applications to monitor and (remotely) diagnose machine condition and failure; and 6) standards for smart sensor interfaces, wireless sensor connectivity, and sensor network capability relevant to condition monitoring.Results in each of these areas are used to realize smart machine tool capabilities of increasing sophistication, demonstrated on a turning and a machining center.

Customers and Collaborators

- AEPTEC
- Agilent
- API
- Boeing
- Caterpillar
- Endevco
- EPRI-PEAC
- Ford
- General Motors
- Hardinge
- Heidenhain
- IQL
- Kistler Instruments
- Lion Precision
- MIMOSA
- NASA
- Northrop Grumman
- Optodyne
- Pratt & Whitney
- Renishaw
- Southern University
- U.S. Army Picatinny Arsenal
- University of North Carolina at Charlotte
- University of Florida
- University of Massachussets
- UNOVA
- VulcanCraft
- Wilcoxon

SURFACE METROLOGY

Program Manager:	Theodore Vorburger
Phone:	301 975 3493
Email:	tvtv@nist.gov
FTEs:	8.5
Program Funding:	$887 K

Program Goal

Deliver with world-leading levels of uncertainty to the U.S. metalworking and semiconductor industries and to the law enforcement community the most critical measurement service or standard required by each in the field of surface and micrometrology.

Problem

The functional properties of many engineering components are affected by surface quality. Therefore, many of these products must be specified and measured for surface finish and microscopic surface feature dimensions. The well-being of U.S. manufacturing relies strongly on continuous improvement in the accuracy of industrial surface metrology, which in turn depends on NIST measurements with ever-lower uncertainty over an increasing range of surface parameters.

Approach

We provide calibrations and tests, standard reference materials, and expertise on documentary standards committees in support of improved surface finish metrology and micometrology in United States industry and government. We use high-resolution profiling instruments, calibrated with respect to the Systeme Internationale d'Unites (SI) unit of length, to perform traceable measurements having low uncertainty. Using new techniques, we are continuously upgrading the accuracy of these instruments and the calibration of our master artifacts to meet developing customer requirements.

Three stages in the manufacture of standard bullets: From left to right, fired master, numerically controlled (NC) machined brass prototype, and NC machined Reference Material 8240

Customers and Collaborators

- American Society of Mechanical Engineers
- Boeing Corporation
- Bureau of Alcohol, Tobacco, & Firearms
- Cummins Engine Company
- IBM Almaden Research Center
- International SEMATECH
- National Institute of Justice
- Veeco Instruments
- VLSI Standards, Inc

SIMA

Program Manager:	James E. Fowler
Phone:	301 975 3180
Email:	jefowler@nist.gov
FTEs:	2.9 (program management)
Program Funding:	$11,752 K

Program Goal

Reduce time-to-market for highly engineered products by improving the productivity of engineering and manufacturing through the widespread adoption of information standards.

Problem

The inability to freely exchange design and production information throughout the supply chain exacts a multi-billion dollar toll on U.S. manufacturing every year. The Systems Integration for Manufacturing Applications (SIMA) Program contributes to the development and testing of standards to improve the exchange of technical data, ultimately aiming to allow data to be shared easily, accurately, and routinely among business activities.

Approach

The SIMA Program sponsors technical research throughout all NIST's laboratory units. SIMA technical research is carried out to establish rigorous methods for defining and testing interoperability solutions, standards specifying information to be exchanged and the interface mechanisms necessary to do so, and tests validating potential standards solutions and implementations.

SIMA supports research in each of NIST's laboratories

Customers and Collaborators

- Aerospace Industry
- Automotive Industry
- Construction Industry
- Electronics Industry
- Engineered Materials Industry
- Genomics Industry
- Industrial Equipment Industry
- Pharmaceutical Industry
- Power Industry
- Process Industry
- Software Vendors
- Standards Development

The various external organizations that participate in SIMA Program research are listed at http://www.mel.nist.gov/div826/msid/sima/collabs.htm.

Programs

MEL Program-Division Cross-Reference Chart

● Primary
○ Secondary

Programs	MEL PED	MEL MMD	MEL MSID	MEL ISD	MEL FTD	NIST PL	NIST EEEL	NIST MSEL	NIST ITL	NIST CSTL	NIST BFRL	NIST TS	NIST MEP	NIST ATP
Advanced Optics Metrology	○	●			○	○	○							
Critical Infrastructure Protection: Cybersecurity of Industrial Control Systems		○	○	●			○		○		○			
Engineering Metrology	●					○	○							○
Integrated Nano-to-Millimeter Manufacturing	○	○	●	○	○		○	○		○	○			
Intelligent Control of Mobility Systems				●							○			
Intelligent Open Architecture Control of Manufacturing Systems	○	○	○	●	○									○
Large-Scale Metrology	●	○	○	○	○						○			○
Manufacturing Enterprise Integration			●	○			○		○		○		○	○
Manufacturing Simulation and Visualization			●		○		○		○		○			○
Mechanical Metrology		●			○		○		○	○	○	○		
Nanometer-Scale Metrology	●	○	○	○	○	○	○	○	○	○	○	○		○
Predictive Process Engineering		●	○	○	○	○		○	○					○
Product Engineering			●											
Shop Floor as a National Measurement Institute	●	○	○	○										
Smart Machine Tools	○	●	○	○	○									○
Surface Metrology	●	○			○		○	○			○	○		
Systems Integration for Manufacturing Applications	○	○	●	○		○	○	○	○	○	○			

Advanced Optics Metrology

Program Manager:
Clayton Teague (Acting)

FTEs:	3.0
Program Funding:	$556 K

FY2003 Projects:

- Report and Demonstration to International SEMATECH (ISMT)
- Uncertainty Analysis for Optical Measurements of Radius of Curvature
- Photomask blank interferometry

Program Goal

By 2005, enhance the competitiveness of the highly leveraged U.S. optics business, and hence multi-billion dollar strategic and commercial sectors such as integrated circuits (IC) production, by developing and providing NIST measurement services for flatness, optical figure, and radius of curvature with Systeme Internationale d'Unites (SI)-traceable expanded uncertainties of 0.25 nm rms or better over apertures up to 300 mm.

Customer Needs

The optics industry has a global reach and substantial domestic impact. Optics is a critical enabling technology for fabricating microelectronic chips, hard disk drive read/write heads, micro-electro-mechanical systems (MEMS), and a growing array of digital displays and cameras. Modern optics are critical to digital cameras, flat panel displays, compact discs (CDs), and digital video discs (DVDs). Missile defense, night vision systems, infrared (IR) seekers, and many other defense systems depend on precision optics made by an industry for which there is effectively no metrological infrastructure.

The need for standards is evident in the microelectronics industry, which contributes an estimated $150 billion to the U.S. Gross National Product. The drive to ever-finer IC features demands diffraction-limited imaging at ever-shorter wavelengths. Leading-edge steppers operate at a wavelength of 193 nm, and require a wavefront better than 16 nm rms for adequate imaging. This net wavefront error must be shared between the surface errors of as many as 20 lenses, assembly tolerances, and materials inhomogenieties. Next generation ICs will require the use of lithographic systems that use ever-shorter wavelengths and have smaller depth of focus and tighter tolerances on lens surface geometry. So wafers on the chuck of the stepper or other tool need ever-improved flatness. No U.S. SI-traceable metrology system is in place for measuring optical figure, wavefront distortions, or wafer flatness; few industry standards exist, and those that do are often outdated.

The International Technology Roadmap for Semiconductors shows optical lithography continuing through the 157-nm generation. The follow-on technology is not known, but the Next Generation Lithography

Workshop, sponsored by International SEMATECH (ISMT), identified Extreme-Ultraviolet Lithography (EUVL) as leading contender. EUVL is likely to be the lithography of choice for ICs with 70 nm linewidths, and it is scheduled to move from the research phase to product development in 2005. But EUVL operates at 11 nm to 13 nm, and demands optics with figure accuracies better than 0.25 nm rms. Today, no U.S. SI-traceable measurements are available. At this low uncertainty level, traceability through transfer artifacts may be untenable; measurement methods must be developed to allow users to make traceable measurements in their own facilities without reference to external authorities.

Meanwhile, consumer products such as digital cameras and DVDs are driving the optics industry to use small, fast aspheric optics. Several attendees at the American Society for Precision Engineering (ASPE) meeting on Precision Interferometry in May 2000 identified traceable measurement of aspheric optics as a key need. Traceability here would be limited to valid uncertainty statements, which are rare in the U.S. optics industry. Currently uncertainty statements for "typical" measurements set-ups compliant with the ISO Guide to Uncertainty in Measurements do not exist.

The performance of optical systems is strongly dependent on the precise radii of curvature of the refractive or reflective surfaces. Indeed, the ability to model optical performance is limited by knowledge of these radii. There is currently no standard test method or a NIST measurement service for such radii of curvature.

Precise optical figure metrology is an issue for a range of "frontiers of science" projects. The Laser Interferometric Gravitational-wave Observatory (LIGO), funded by the National Science Foundation, uses optics with specifications close to those for EUVL. NIST measurements were crucial to the development of the first observatory and it is expected that more support will be needed for the upgrade planned for 2005. The metrology needs of the National Aeronautics and Space Administration (NASA) include support for the Space Interferometer and Next Generation Telescope projects. The Department of Enery (DOE) National Ignition Facility (NIF), by contrast, requires NIST metrology support for high volumes of optics. The NIF will use 8000 large (>400 mm) optics and 30,000 smaller optics; validation of vendor metrology methods will eliminate the need for inspection of all deliverables, but this approach demands NIST traceability and, hence, defensible uncertainty statements at every vendor.

Technical Approach

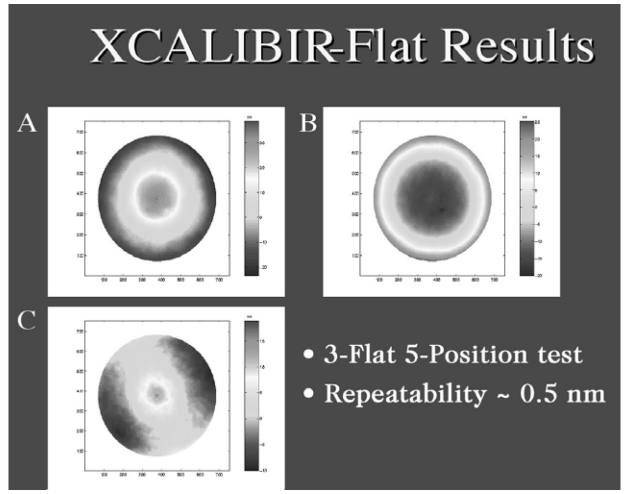
Phase measuring interferomters (PMIs) are used to measure optical figure. Commercially available PMIs can be extremely repeatable; an array of techniques, including some developed in this NIST program, are now available for separating part errors from the signature of the instrument—at least for some classes of surfaces. By using such approaches we showed that PMIs could provide measurement uncertainties of the order of 1 nm for flats and near-flats such as the LIGO optics. Higher uncertainties are obtained in the measurement of spherical optics. We will continue to develop measurement methods and error separation techniques to reduce the uncertainties of measurements made with commercially available PMIs. Also, we will develop, implement, and validate measurement techniques to enable users to characterize instrument performance.

For the measurement of aspheric optics (i.e., systematic deviations from a base sphere) such as those needed for EUVL, there are some basic limitations to the potential of commercially available PMIs. Concepts for a system combining a PMI with high-precision slideways have been developed and implemented (in collaboration with an industrial vendor) in a new measurement capability, the NIST X-ray accurate optics CALIBration InterferometeR (XCALIBIR). Designed to have the flexibility to measure flats, spherical, and aspheric optics, XCALIBIR was installed at NIST in FY1999 and is still being refined. The measurement goal is 0.25 nm rms uncertainty in measurement of aspheric optics up to 300 mm diameter with focal lengths up to 2 meters. A measurement service is bsing developed based on this capability.

Interferometric tests can be used to measure not only the departure of a surface from the best-fit sphere, but also other important features of optical components. Examples include the radius of curvature of that sphere or the refractive index and its local variation. Currently, NIST offers no measurement service for radii and there is no rigorous analysis in the literature to help instrument users assess uncertainties in their own measurements of radius. XCALIBIR will be used to address these problems and the results compared to those achieved with mechanical measurements.

Measurement of as-chucked wafer flatness requires separation of chuck-induced errors from wafer thickness variations. NIST is establishing reference optical instruments that will provide traceable measurements. XCALIBIR is able to measure 300 mm flats directly. Wafer thickness variation can be measured in a NIST-patented interferometer operating at 1.55 µm. A 300 mm commercial implementation of the system has been installed, and new measurement procedures are now being developed.

At the limits of precision or size, advanced users can minimize uncertainties by implementing, in their own facilities, measurement strategies and procedures developed and validated at NIST.In this way, they can obtain a defensible uncertainty budget, without reference to any "external" authority. In the case of large optics, NIST will support NASA's development of an in-house capability to make traceable measurements on optics larger than 400 mm aperture at the Marshall Space Flight Center.



Program Objectives and Technical Outputs

Objective 1:

By 2004, develop methods for reference measurements of wafer thickness, thickness variation, and bow and demonstrate these to appropriate representatives from ISMT.

Technical Outputs

FY2003:
Evaluation of the spherical wavefront Haidinger fringe method for thickness, thickness variation, and bow on wafers up to 300 mm and results reported at an ISMT Working Group or ISMT-sponsored workshop.

FY2004:
Development of uncertainty analysis, publication of results, and demonstration of operation for ISMT.

Objective 2:

By 2004, develop and complete experimental and theoretical studies for determination of expanded uncertainty for measurements of radius of curvature for optics and reference spheres.

Technical Outputs

FY2003:
Comparison of mechanical and optical measurements of radius of curvature and resolution of any discrepancies.

FY2003:
Complete uncertainty analysis for optical measurements of radius of curvature published.

Objective 3:

By 2005, complete and publish documentation on XCALIBIR instrumentation and measurement procedures for flats and spherical optics.

Technical Outputs

FY2003:
Initial ray-trace analysis of XCALIBIR optics and instrumentation completed.

FY2003:
Type A & B uncertainties of NIST-developed procedures and instrumentation for measuring flats and spherical optics up to 300 mm in diameter determined.

FY2004:
A published report on work of previous output and demonstration of measurements on NIST owned and/or customer supplied flat and spherical optical surfaces in accord with a report to appropriate representatives from the advanced optics industry.

Objective 4:

By 2005, plan and conduct key comparisons for measurements of flats, spherical and aspheric optics with other National Measurement Institutes (NMIs).

Technical Outputs

FY2003:
A report on full ray-trace analysis of XCALIBIR optics published.

FY2004:
A report on determination of the type A & B uncertainties of NIST-developed procedures and instrumentation for measuring aspheric optics up to 300 mm in diameter and with focal lengths up to 2 m published.

FY2004: All measurements for NIST contribution to key comparison completed.

Objective 5:

By 2006, as indicated by workshop with expected customers, publish all necessary documentation for initiation of calibration services for optical flats and a range of spherical reference optics.

Technical Outputs

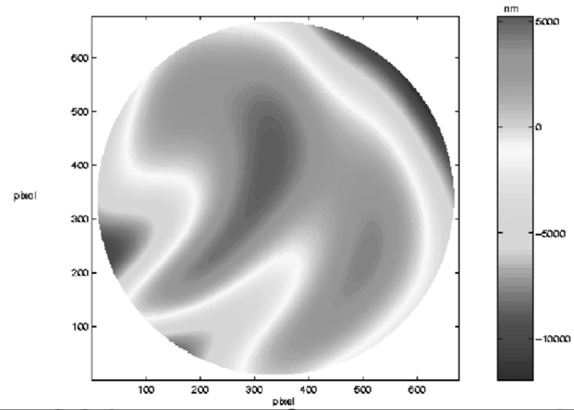
FY2005:
Workshop with expected customers of a NIST calibration for flats, spheres, and mild aspheres held and most appropriate means to meet customer needs for these measurements determined.

FY2005:
Instrument description, recommended measurement procedures, and generic uncertainty statements for interferometric measurement of flats, spheres and mild aspheres sufficient to enable a user to replicate NIST measurements with equivalent uncertainties published.

FY2005:
A published report describing results of key comparisons with colleagues from other (NMIs).

Accomplishments of the Past Year

- Completed 3-flat tests with XCALIBIR for 300 mm diameter flats with 0.5 nm repeatability.
- Measured flatness of unconstrained 200mm and 300 mm diameter silicon wafers with XCALIBIR.
- Implemented digital image filtering methods that enable the evaluation of silicon wafer topography measurements at different spatial frequencies.
- Designed and built a diamond turned wafer chuck for measurements of chucked wafer flatness with XCALIBIR. Made initial measurements of chucked wafers with XCALIBIR.
- Devised and implemented new, comprehensive alignment procedures for radius-of-curvature measurements with XCALIBIR.
- Automated radius of curvature measurements with XCALIBIR to reduce the time needed for a measurement by one order of magnitude.
- Analyzed uncertainties in radius of curvature measurements with XCALIBIR and implemented the results in data analysis software for radius measurements.
- Carried out several radius of curvature and figure measurements on a 93 mm diameter ultra-precise silicon sphere that is a potential density or mass standard.



200mm wafer measured with XCALIBIR

Anticipated Impacts

We anticipated that a successful program will have the following impacts:

(1) Adoption by the optics industry, microelectronic fabrication industry, and major national science projects from agencies such as NASA of the measurement methods developed and validated by NIST for characterizing photomask blanks, semiconductor wafers, substrates for large liquid crystal display (LCD) panels, and critical optics.

(2) Incorporation of the measurement methods developed under this program into procurement specifications by these same industries to minimize controversy over measurement results and compliance with specifications.

(3) To meet the needs in which customers prefer an “external” authority for reasons of economy or resource limitations, a NIST measurement service for flatness, optical figure, and radius of curvature will be available where none now exist.

Other Information

The resources of this program are highly leveraged. We work closely with the NIST Physics Laboratory on complimentary aspects of EUV optics and collaborate closely with all researchers involved with the NIST Office of Microelectronics Programs on related optical projects for the microelectronics industry. Shared staff, instrumentation, laboratories, and facilities from industry and other government agencies have been an ongoing part of this program. These include contracts with government laboratories such as the DOE Lawrence Livermore National Laboratory; and industrial organizations, including: the EUV Limited Liability Consortium and the Optical Perspective Group. We collaborate with Schott Glass (U.S. and Germany), SVG Tinsley (U.S. and Netherlands), Tropel Corporation, and Zygo Corporation. In addition, we are working closely with ISMT Working Groups and the SEMI Advanced Wafer Geometry Task Force.

Standards Participation

As noted in the Customer Need section, few standards exist, and those that do are outdated. We have been working with appropriate industry groups such as SEMI to initiate standards for the measurement of wafer geometry and others for radius of curvature.

Critical Infrastructure Protection

Program Manager:
Fred Proctor

FTEs:	1.5
Program Funding:	$433 K

FY2003 Projects

Test Methodology Validation

Protection Profiles

Program Goal

By 2007, increase the security of computer systems that control production and distribution in critical infrastructure industries, including electric power, oil and gas, water, chemicals, pharmaceuticals, metals and mining, pulp and paper, and durable goods manufacturing by (1) defining and applying standard information security requirements, (2) developing information security best practice guidelines and conducting outreach activities, and (3) developing laboratory and field test methods for information security products and approaches applied to the process control sector.

Customer Needs

The computer systems that control industrial production and distribution have been designed first and foremost to meet performance, reliability, safety, and flexibility requirements. Yet these systems increasingly incorporate connectivity and remote access capabilities. Industry has begun to appreciate that increased connectivity and openness are introducing serious vulnerabilities into their operational systems. One critical problem of immediate concern is the absence of methods to specify and verify the security characteristics of control system components and networks. These are problems that the Common Criteria for Information Technology (IT) Security Evaluation, developed by NIST and the National Security Agency (NSA), are intended to address.

Power plants such as this form the nation's critical infrastructure. Securing them against cyberattack is a top priority.

Technical Approach

To develop IT security requirements for industrial control systems, NIST leads the Process Control Security Requirements Forum (PCSRF), a working group comprised of vendors and users of process control automation. The PCSRF was formed under the umbrella of the NIST/National Security Agency National Information Assurance Partnership (NIAP). The PCSRF includes participation from Electric Power Research Institute (EPRI); the Instrumentation Systems and Automation Society (ISA); Sandia and other Department of Energy (DOE) Labs, the American Gas Association (AGA); Institute for Gas Technology (IGT); Association of Metropolitan Water Agencies (AMWA), the Open Group, Institute for Electronic and Electrical Engineers (IEEE), the National Center for Manufacturing Sciences (NCMS), and individual companies. Through the PCSRF, the following steps are being taken to develop process control information security requirements:

- currently available computer control system architectures, including analysis of threats and vulnerabilities;
- develop information security requirements, in a language and format understandable to the process control users and vendors; and
- translate Information Security Requirements into Common Criteria, the international standard ISO 15408, Protection Profiles that can be used to enable testing and evaluation of covered computer control system products/systems by accredited IT security testing laboratories.

Program Objectives and Technical Outputs

Objective 1:

By FY2003, publish Security Profile Specification (SPS) document that lists requirements for process control security across CIP industries and for selected domains such as chemical processing, oil and gas, electricity and water. Draft accompanying Protection Profiles according to the ISO 15408 Common Criteria.

Technical Outputs

FY2003:
The Security Profile Specification document published.

FY2003:
Protection Profiles drafted.

Objective 2:

By FY2004, develop laboratory and field test methods for information security approaches and products applied to the process control industry. These methods should (1) check the security of secure components when they are combined into systems and used in the context of an integrated enterprise, and (2) test the effectiveness of information security best practices guidelines.

Technical Output

FY2004:
Technical report detailing laboratory and field test methods for information security approaches and products in process control industry.

Accomplishments of the Past Year

Distributed control testbed established

This testbed includes components from process control automation typical of the utility industries, including device networks and Supervisory Control and Data Acquisition (SCADA) systems.

Security Profile Specification document drafted

This document contains requirements articulated by the PCSRF members, focusing on electrical power and natural gas distribution.

Standards Participation

Process Control Security Requirements Forum (PCSRF)

The PCSRF is a group of industrial control systems users, vendors, and industry organizations that is developing standard IT security requirements for computers and components used in industrial production and distribution. It is organized under the NIAP and is applying the Common Criteria for IT Security Evaluation (ISO/ International Electrotechnical Commission (IEC) 15408) in developing these requirements. NIST is leading this group and providing contracted requirements engineering support to it.

American Gas Association (AGA) SCADA Encryption Committee

This committee is working to identify appropriate cryptographic means to secure SCADA communications and draft corresponding guidelines/standards for the utilities industries. NIST's activity includes reviewing and contributing to draft specifications and providing information and guidance regarding applicable encryption standards and testing programs.

The Instrumentation, Systems, and Automation Society (ISA) SP99 Manufacturing and Control Systems Security Committee

This committee is working on ISA standards for secure process control automation. We expect our work to be complementary, providing SP99 with security requirements for which ISA will provide an avenue for formal standardization.

Program Manager:
Ted Doiron

FTE:	8.2
Program Funding:	$1300 K

FY2003 Projects

- Small Hole Geometry
- Characterization of Thermal Expansion
- High Accuracy Video Measurements

ENGINEERING METROLOGY

Program Goal

By 2005, provide world-class engineering metrology resources for our customers to promote the health and growth of U.S. manufacturing by:

- delivering significantly improved, state-of-art uncertainty levels for industry-critical measurement services, reducing key uncertainties by factors of two or more;
- reducing calibration turn-around time (by 15 percent or more) and increasing percentage of calibrations completed on time (by 25 percent or more) in key calibration areas, while simultaneously reducing NIST resources required to support less-needed calibrations;
- promoting alternate routes to traceability that minimize need for NIST measurements; and
- developing new measurement techniques to meet emerging industry needs.

Customer Needs

Engineering Metrology includes a variety of length and geometric measurements of objects with characteristic dimensions that range from a fraction of a millimeter to more than a meter. This program supports a very broad spectrum of customers including national and international manufacturers, research and calibration facilities, standards writing organizations, and academia. Our principal commercial customers are the automotive, heavy equipment, telecommunications, and aerospace industries. These customers need (1) traceable measurements and standard reference materials with the lowest attainable uncertainty and (2) development of new techniques to improve and extend measurement capabilities.

Provision of world-class measurement services is central to this program and is important to our customers. Artifacts calibrated by MEL provide a direct path of traceability of industry measurements to the international standard of length – the meter. The calibrated artifacts are used as measurement reference standards to ensure that the dimensions of manufactured parts meet their design specifications. When manufactured parts conform to their design specifications - and such conformance is verified by traceable measurements - they work better, last longer, can be properly assembled with parts manufactured at other companies throughout the nation and the world, and can meet requirements for international trade. MEL annually calibrates over 5000 dimensional artifacts for over 160 organizations in 40 states. MEL calibrations are the keystone in assuring traceable measurements for the US manufacturing sector; they establish a direct, straightforward, and convincing path of traceability to international standards.

Research into new measuring techniques is an important part of this program. Today's global economy requires that we continuously improve our dimensional measurement capabilities to satisfy the demands of ever-tightening tolerances and to maintain parity with other national measurement institutes (NMI). The verifiable accuracy with which a part or instrument can be sold in the international marketplace will in some cases depend on the uncertainty of our calibrations, and therefore it is important to U.S. manufacturers that these calibrations be delivered with best-in-the-world capabilities.

New measurement techniques developed at NIST and improvements in our internal measuring capabilities will have direct economic benefits for our customers by allowing them to explore areas of design and development previously unapproachable due to measurement limitations. For example, a variety of industrial sectors would benefit from improvements in our capability to measure the diameter and form of small holes and other small structures; we have seen a number of inquiries and demand for measurements of small holes or small structures including optical fiber ferrules, optical-network switching elements, cleavage-angle on optical fibers, fuel injectors, slider assemblies for magnetic storage, and millimeter-connectors and precision offset shorts for high frequency microwave systems. Similarly, we see significant industry demand for better measurement of cylindrical artifact geometry beyond what we can currently deliver. (This is also a limiting factor in the uncertainty of the NIST realization of the derived unit of pressure; both cylindrical form and ultra-high accuracy diameter measurements are needed.) We also need to develop new measuring techniques to improve the efficiency with which we can deliver existing measurements - and we need to encourage adoption of these techniques by calibration labs in both the government and private industry.

Technical Approach

This program takes a broad approach to improving all aspects of Engineering Metrology services to industry, an approach based on delivery of high-quality measurement services coupled with research into new measuring methods. An important element of our long-term planning is concentration of resources into key areas. This concentration of effort will require that less-important measurement services are either terminated or are operated with no investment of NIST appropriated funding. In areas where resources are concentrated, we are carrying out research to improve our own measurement capabilities and to develop industry-needed processes. The immediate goals of this effort are to lower measurement uncertainty, expand measurement range, and increase measurement efficiency.

Program Objectives and Technical Outputs

Objective 1:

By FY2004, extend the range of capabilities for industry-needed measurements of small, high-relief structures (such as 125 mm holes), with nano-force probing.

Technical Outputs

FY2003:
Characterization of current prototype small hole (< 100 µm diameter) contact probe system and test prototype against 0.5 mm holes that can be calibrated accurately on the M48 coordinate measuring machine (CMM).

FY 2003:
Exploration of use of micro-electromechanical systems (MEMS) types of probes for small holes.

FY 2004:
Modified probe to measure in 2-dimensional designed and fabricated.

Objective 2:

By FY2005, develop systems for state-of-art cylindrical form measurement.

Technical Outputs

FY2003:
Performance studies of new state-of-the-art cylindricity instrument provided through an industry cooperative research and development agreement (CRADA).

FY2004:
Comparison of roundness and cylindricity algorithms used in industry, and studies to develop standard uncertainty budgets for these methods.

FY2005:
Published report of form measurement techniques developed by program staff members using one or more techniques to achieve state-of-art results.

Objective 3:

By FY2005, demonstrate world-class (sub-100 nm uncertainty) 2-dimensional video-based CMM measurements

Technical Outputs

FY2003:
A video-based CMM system to measure large grid plates with uncertainties below 200 nm premiered.

FY2004:
Papers describing video measurements of grid plates and other video-based CMM measurements of relevance to technologies such as optical fiber connectors and printed wiring board published.

FY2005:
A prototype commercializable probe system developed and installed on CMM.

Objective 4:

By FY2004, finish development and implement new systems for gauge block and sphere calibration to improve calibration efficiency by reducing the number of needed master artifacts. The targets are a 50 percent reduction for gage blocks and more than 80 percent reduction for spheres.

Technical Outputs

FY2003:
Calibrated calibration set of gauge blocks with known mechanical length differences, along with a detailed uncertainty budget.
Gauge block calibration service based on single set of master blocks, thus eliminating half of our master blocks.

FY2003:
Prototype flexible laser-based micrometer for efficient sphere/wire/cylinder diameter measurements delivered to Army.

FY2004:
New micrometer-based sphere calibration system.

Objective 5:

By FY2004, provide industry with needed thermal expansion coefficients of characteristic, key artifacts, measured with our new system for high-accuracy dilatometry.

Technical Outputs

FY2003:
Third prototype dilatometer finished and measurement of values for thermal expansion of important artifacts such as grid plates began.

FY2003:
Paper describing dilatometer system, measurement uncertainty, and results for characteristic artifacts

FY2004:
Thermal enclosure of dilatometer improved to provide extended range and capability.

Objective 6:

By FY2004, lead key and regional comparisons and perform needed measurements to provide technical basis for international acceptance of NIST measurements under the Mutual Recognition Agreement (MRA).

Technical Outputs

FY2003:
Final measurements as pilot lab for the Consultative Committee for Length (CCL) diameter key comparison and completion of first-draft report.

FY2003:
Protocols for Interamerican System of Metrology (SIM) regional diameter comparison completed and published.

FY2004:
Final CCL diameter report published.

FY2004:
Measurements completed for SIM regional diameter comparison.

Objective 7:

By FY2005, timely provision of measurement services: Reduced turn-around time, achieved through concentration of efforts with elimination of less-needed calibration services

Technical Outputs

FY2003:
Announcement of the end of the penetration needles and sieves measurement services ended within constraints of regulatory laws and of NIST/Department of Commerce (DOC) policies.

FY2004:
Two additional calibrations services ended.

FY2004:
Turn-around time reduced by 15 percent and fraction of calibrations completed on time increased by 25 percent

Objective 8:

By FY2005, develop techniques to quantify camera metrology and provide materials (grid SRM) needed to improve 2-dimensional metrology in semiconductor manufacture

Technical Outputs

FY2003:
Issuance of SRM with state-of-the-art measurement uncertainty for 2-dimensional metrology.

FY2005:
Papers describing camera metrology errors and the methodology for camera testing published.

Anticipated Impacts

As the top of the traceability chain, NIST measurements of dimensional artifacts have a highly leveraged impact on the economy. For example, the 4,000,000 gauge blocks under measurement control in the U.S. are almost all part of a measurement hierarchy directly or indirectly based on NIST gauge block calibrations— and these 4,000,000 blocks are responsible for a large part of the dimensional measurement infrastructure that guarantees interchangeability of parts. Although quantitative impact is difficult to estimate in detail, it is clear that our measurements play a very significant role throughout the U.S. manufacturing sector, and that even a very small fractional effect on this multi-billion dollar segment of the economy would represent tremendous added value. Improved service to our customers will enhance U.S. ability to compete in world markets and to produce properly functioning parts. New measurement techniques developed at NIST, expanding the range of measurements we can deliver, will provide opportunities for advances in areas with unmet measurement needs such as those enumerated in the section above.

Accomplishments of the Past Year

AAMACS used in International Key Comparison

We demonstrated the ability of the NIST Advanced Automated Master Angle Calibration System (AAMACS) through participation in the International Key Comparison for angles. Additional measurements were made on our traditional equipment as a check on the standard. We also demonstrated the use of the ZYGO Phase Shifting Interferometer (PSI) as an autocollimator by simultaneous measurements using the PSI and our high accuracy autocollimator.

High Accuracy M48 CMM begins grid plate calibrations

We completed the integration of the computer vision system to our M48 operating system. Initial tests on well-characterized gridplates (140 mm square) show the expanded uncertainty (k=2) to be below 100 nanometers. We developed a new vision system to replace the 1986 system currently in use.

Measurements of Diameter of two Silicon Spheres agree with CSIRO within 10 nanometers

Two single crystal silicon spheres made by the Commonwealth Scientific and Industrial Research Organization (CSIRO), the Australian NMI, were measured on the M48 CMM. The spheres were also measured at CSIRO in a specially built Saunders-type interferometer. Both spheres were measured at multiple positions in the CMM volume, and in multiple orientations. The standard deviations of the diameter of the rounder sphere measured in nine positions and twelve orientations was 27 nm, and the expanded uncertainty of the average diameter is estimated to be 30 nm. The average diameters of the spheres measured by the two methods differed by 2 nm and 10 nm. The closeness of the two sets of data from extremely different measurement methods gives us significant confidence in the results, as well as important verification of the M48 accuracy.

CRADA signed with Mitutoyo USA for cylindricity studies

We signed a CRADA with Mitutoyo, a leading manufacturer of metrology instrumentation, to study methods for roundness, straightness, and cylindricity measurements. As part of this agreement, we were loaned the latest state-of-the-art instrument for the studies, and have already begun to study calibration methods and alternative error compensation methods. The studies will eventually encompass a thorough review of the current industry practices, and the development of methods based on the most current research in algorithm design and uncertainty estimation techniques.

Calibrations in Provide Needed Service to Industry

We reduced calibration turn-around time during the last calendar year in spite of an increased calibration load.

Service to Industrial Metrologists

The Engineering Metrology Toolbox, located on the MEL web site, provides our customers with practical metrology information and computational tools. It was featured in an article appearing in the August 2002 issue of Quality Magazine. The Quality article discusses our web-based tools that perform: (1) deformation of surfaces under contact forces; (2) air refractive index calculated from pressure, temperature, and humidity; and (3) an online tutorial describing thermal expansion effects. In FY2003, we are planning on placing a large number of informational and tutorial documents developed over the years by MEL staff members on the site as downloadable files.

Silicon sphere fixtured on M48 CMM

Key Comparison of Diameter Standards Begins Final Phase

NIST is the pilot laboratory for the CCL-K4 key comparison for internal and external diameter measurement. The comparison recently began its last cycle, which will be followed by re-measurement of the artifacts here at the pilot laboratory. The CCL key comparisons provide the technical basis for the MRA between NMIs, which is intended to reduce barriers to international trade.

M48 Calibration of Long End Standards

The staff of the Engineering Metrology and Nanoscale Metrology programs participated in the international Key Comparison of long end standards. At the same time the standards were measured on the our M48 CMM. The draft report of the Comparison has been circulated to committee members and the M48 results helped validate the uncertainty budget currently used for 1-dimensional end standards. We began an informal comparison of step gauge measurements with a number of Department of Energy (DOE) laboratories and the Canadian National Research Council lab.

Progress in Grid Plate SRM

The first batch of five plates was completed and delivered to the Office of Standard Reference Materials (SRM). These plates were measured by a state-of-the-art 2-dimensional mask-measuring machine, and two lines of each plate were calibrated by the NIST Linescale interferometer. Extensive measurement of the plates in multiple orientations and the comparison of the scale to the NIST Linescale allowed us to develop an uncertainty budget based primarily on the statistical analysis of data (Type A estimation), thus reducing the dependence on subjective probability (Type B estimation).

Workshops

Members of the Engineering Metrology Group Present Four Papers at Measurement Science Conference

Jack Stone, John Stoup, Eric Stanfield, and Ted Doiron presented papers at the Measurement Science Conference in Anaheim, CA. The papers reported on recent progress our group made in the measurement of small holes, improvement in the performance of the M48 CMM, our work in thread form measurements, and a new proposed system for deformation corrections in our gauge block calibrations.

Work on Metrology of CCD Subpixel sensitivity presented at IDW 2002

A report of early studies of the subpixel sensitivity of a Charge-Coupled Device (CCD) video camera was presented at the International Dimensional Workshop in Knoxville, TN. The early work shows the active area of many cameras is very small. The report discussed the implications of this in the use of subpixel edge-finding algorithms.

Standards Participation

New ASME Gauge Block Standard Published

A 10-year effort to harmonize the U.S. Gauge Block Standard (ASME B89.1.9) to the internationally accepted ISO 3650 was completed in 2002. This is the first change in the basic standard in over 40 years. Members of the Engineering Metrology Group played a significant part in making this happen, including the hold the role of Chairman, during the entire effort.

- American Society of Mechanical Engineers (ASME) B89: Dimensional Metrology
- ASME B1.8 Stub Acme Screw Thread - Chairman
- ASME B89.1.17 Thread Wire Measurement - member
- ASME B89.1.2 Calibration of Gage Blocks by Mechanical Comparison - member
- ASME B89.1.5 Measurement of Plain External Diameters for Use as Master or Cylindrical Plug Gages - member
- ASME B89.1.6 Measurement of Qualified Plain Internal Diameters for Use as Master Rings and Ring Gages - member
- ASME B89.1.8 Laser Interferometers - member
- ASME B89.1.9 Gage Blocks - Chairman
- ASME B89.3.1 Roundness - member
- ASME B89.5 Vocabulary - member
- ASME B89.7 Measurement Uncertainty - member
- Consultative Committee for Length (CCL) of the BIPM - member
- Working Group on Dimensional Metrology of the CCL - SIM representative to working group

FY2003 Measurement Services

• (10010C-10015C)	Gage Blocks
• (10060S)	Sieves
• (10010S-11014S)	Cylindrical Diameter Standards
• (11020C-11021C)	Thread Wires
• (11030S-11034S)	Spherical Diameter Standards
• (11040S-11041S)	Plain Ring Gages
• (11060S)	Step Gages
• (12010C-12042C)	API Gages
• (12050S)	Threaded Plug and Ring Gages
• (12060S)	Two Dimensional Gages
• (12070S)	Complex Dimensional Gages
• (13010S-13014S)	Optical Reference Panes (Flats)
• (13020S-13030S)	Roundness
• (14010C-14011C)	Angle Blocks
• (14020S)	Polygons
• (14030S-14031S)	Indexing Tables
• (14040S-14041S)	Optical Wedges
• (14050S)	Special Angular Measurements
• (14510S-14511S)	Laser Frequency/Wavelength

SRM

- SRM 2522 Pin Gage Standard for Optical Fiber Ferrules
- SRM 2523 Optical Fiber Ferrule Geometry Standard
- SRM 2553 Optical Fiber Coating Diameter (n=1.504)
- SRM 2554 Optical Fiber Coating Diameter (n=1.515)
- SRM 2555 Optical Fiber Coating Diameter (n=1.535) (sold out)

Program Manager:
Kevin W. Lyons

FTEs:	9.25
Program Funding:	$883 K

FY2003 Projects

- Atomic scale manufacturing
- Molecular scale manipulation and assembly
- Micro-to-millimeter scale manufacturing technologies

INTEGRATED NANO-TO-MILLIMETER MANUFACTURING TECHNOLOGIES

Program Goal

Address the anticipated needs of the U.S. nanotechnology industry; develop and deliver models, architectures, and methods for process measurement and control systems that enable manufacturing across nm-to-mm scales.

Customer Needs

Major industrial and scientific trends that emerged during the 1990s will influence not only how manufacturing will be done over the next decade, but also what is manufactured. The size of many manufactured goods continues to decrease, resulting in ultra-miniature electronic devices and new hybrid technologies. For example, microelectromechanical systems (MEMS) devices integrate physical, chemical, and even biological processes in micro- and millimeter-scale technology packages. MEMS devices now are used in many sectors: information technology (IT), medicine and health, aerospace, automotive, environment and energy, to name a few. On the horizon is the development of nanomanufacturing technologies that will support tailor-made products having functionally critical nanometer-scale dimensions produced using massively parallel systems or self-assembly.

The trend in product miniaturization will require new process measurement and control systems that can span millimeter, micrometer, and nanometer-size scales while accounting for the associated physics that govern the device and environment interaction at each specific size scale. New standardized architecture definitions will be needed that support multiple physics-based models and new computational representations that allow seamless transition and traversing through these various models. System control architectures will need to support human-in-the-loop or automated closed-loop requirements while addressing the coordination and synchronization of multi-modal inputs/outputs through a variety of haptic, visual, audio and other sensory and actuation devices. In addition, research and development

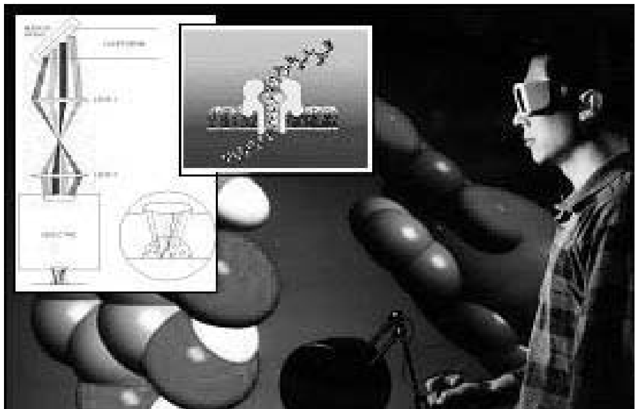
(R&D) focusing on process measurement systems, such as the development of calibration standards, standard reference materials (SRM) manufacturing processes, and SRM distribution procedures, will be necessary. All of these advances, and likely additional ones yet to be identified, will be needed to achieve success in effective analysis and validation of nano-to-millimeter device and process performance

Technical Approach

The research effort comprises three research thrusts, each focused on a specific application area and problem set. The three research thrusts support manufacturing at the atomic, molecular, and micro-millimeter scales and will serve as the mechanism for development of relevant models, architectures, and methods for process measurement and control systems. Throughout all phases of the program, the knowledge learned in each of the thrust areas will be shared with the others to maximize the outcomes of the program. The thrust areas and the associated objectives are:

Atomic scale manufacturing: Develop and assemble the technologies required to fabricate standards that have atomically precise, but pre-determined positions and atomic structure. This will include work directed at solving artifact integrity, precision placement, dimensional metrology, and manufacturing issues.

Molecular scale manipulation and assembly: Identify and address the fundamental measurement, control and standards issues related to manipulation and assembly of micro/nanoscale devices using optical methods. This entails building the manipulation technology and using it to understand and address the measurement issues that arise when assembling devices at the micro/nanoscale level



Program will develop models, architectures, and methods that support improved human-computer interfaces for controlling complex instruments

Micro-to-millimeter scale manufacturing technologies: Develop the technologies required to position, manipulate, assemble, and manufacture across micro-to-mm scales. This will include work directed at micro-positioners, micro-mirror arrays, micro-sensors, micro-actuators, micro-tools, micro-assembly, and micro-manufacturing issues.

Overall, the program seeks to develop standard-based manufacturing architectures, calibration and metrology techniques, and interfaces that meet the expected industrial requirements. Aspects of interest include effective human-computer interfaces, fully deterministic computer system architectures, molecular modeling-to-computer aided design (CAD) exchange formats, advanced control system architectures, image resolution and registration, process models, and advanced signal processing and image analysis. The program also seeks to provide industry with critical methods and technologies that support micro-nanoscale traceability to basic and derived units of measure, including length, mass and force. Expected outputs will include performance metrics for manufacturing equipment and processes, production-hardened calibration methods and supporting hardware and software, and definition and production of SRMs.

Program Objectives and Technical Outputs

Objective 1

By FY2007, develop and assemble the technologies required to fabricate standards that have atomically precise, but pre-determined positions and atomic structure. This will include work directed at solving artifact integrity, precision placement, dimensional metrology, and manufacturing issues.

Technical Outputs

FY2003:
Methods and models that support the accurate prediction of critical atomic force microscopy (AFM) and scanning tunneling microscope (STM) tip dimensions (in a manufacturing context) to maintain product conformance.

FY2005:
Documentation of the performance measurement methods and technologies that support process and manufacturing equipment certification required for industry to meet product yield expectations.

FY2006:
Documentation of methods to fabricate and validate atomic-scale structures with features written directly in atomically-ordered surfaces with atomic clusters composed of known atomic species whose chemical composition can be measured.

FY2007:
SRM suitable for setting up nanoscale manufacturing processes with verifiable dimensional and chemical makeup, thus providing industry the ability to make traceable measurements (e.g., repeatability and identified uncertainties) of position and chemical makeup in a manufacturing-relevant setting.

Objective 2

By FY2007, identify and address the fundamental measurement and standards issues related to manipulation and assembly of micro/nanoscale devices using optical methods. This entails building the manipulation technology and using it to understand the measurement issues that arise when assembling devices at the micro- and nanoscale-level.

Technical Outputs

FY2003:
Virtual Environment (VE) technologies and supporting formal representations that support the display of torque and force interactions between molecules through visual, audio, or haptic modes under the discretion and control of the user.

FY2004:
Optical Instrument (Phase 2) and demonstration of the ability of integrated optical system (e.g., optics, electronics, and software) to trap, manipulate, and measure micrometer and sub-micrometer parts with irregular shapes. This will include initial control interfaces between the physical resources and the virtual environment.

FY2005;
Optical Instrument (Phase 3) and demonstration of integrated heuristic user interface (e.g., VE) for measurement and manipulation of nanodevices. Closed feedback system that links the calculated position/orientation with those displayed in the VE.

FY2007:
Optical Instrument (Phase 4) and demonstration of feasibility by developing methods for achieving traceability of force measurements. Demonstration of these methods through the assembly and measurement of nanodevices from external partners.

Objective 3

By FY2007, develop prototype millimeter and micrometer (i.e., MEMS) devices and associated control systems for precision positioning and force measurements. Incorporate these sub-systems into a measurement system that addresses an industry need such as nano-tribology or spacecraft communications.

Technical Outputs

FY2003:
A fabricated credit card-size high precision micro-positioner based on current flexure design. Identification of pros and cons of optical beam steering technologies for microscopic vision, hazardous environment vision, nano-particle manipulation and spacecraft communications. Calibration and control of micro-mirror array (i.e., MEMS) laser micro-beams. Conceptual design of micro-assembly testbed.

FY2004:
A MEMS force sensor with documentation that captures sets of precision fabrication technologies necessary to achieve required design specifications and tolerances mandated by sensor design. Identification and preliminary solutions for the fundamental issues of micro-assembly using integrated micromanipulation and sensor technologies. Identification of the sensor and control needs of micro-devices in operation critical (e.g., hazardous and medical) environments.

FY2005:
MEMS process technologies and sensor prototypes refined for optimal measurement performance; and a prototype transfer artifact for force. Identification of pros and cons of micro-devices for the manipulation and assembly of nano-particles. Identification of the metrology, actuation, control and calibration issues.

FY2007:
Demonstration of precision positioning and force measurement devices being utilized in a measurement system. (e.g., micro-assembly, spacecraft instrumentation, hazardous devices, medical devices, or nano-tribology)

Anticipated Impacts

The models, architectures, and methods that are developed and demonstrated will serve as catalysts for standardization and promote further development and implementation of process measurement and control systems by industry. An expected outcome will be the continuation of this work by industry and implementation of pilot studies by industry that support the further development of models, architectures, and methods for process measurement and control systems that enable manufacturing across nm-to-mm scales.

More specifically, the program is expected to produce the following outputs and impacts:

- A SRM suitable for setting up nanoscale manufacturing processes with verifiable dimensional and chemical makeup. This will provide industry with the ability to make traceable measurements (repeatability, identified uncertainties, etc.) of position and chemical makeup in a manufacturing-relevant setting. This is critical step in taking product concepts to market.
- A set of VE technologies and draft standards that enable real-time exploration of assembly options from millimeter through nanometer scales.
- A set of technologies that enable traceable measurement (e.g., repeatability and identified uncertainties) of nanoscale device positions, orientations, and forces in manufacturing and product operation environments (i.e., varying humidity, temperature, or aqueous solutions)

- A collection of methods that support performance measures of scanning tunneling microscopes and micro-positioners.
- A documented set of process technologies and design, build, and test variants of positioning systems and force sensors with optimal measurement performance. These will include physical prototypes of candidate force-transfer artifacts and beam-steering micro-positioning devices.

An emphasis will be placed on advancing the state of standards and measurements that will benefit the micro-nanotechnology industry. By developing standard-based manufacturing architectures, calibration and metrology techniques and interfaces, the work will promote:

- effective human-computer interfaces,
- fully deterministic computer systems architecture,
- molecular modeling-to-CAD exchange formats,
- advanced control system architecture,
- image resolution and registration,
- process models, and
- advanced signal processing and image analysis.

By providing with critical methods and technologies to support micro-nanoscale traceability to basic and derived units of measure, including length, mass and force, our work will produce:

- performance metrics for manufacturing equipment and processes,
- production hardened calibration methods and supporting hardware/software, and
- Standard Reference Materials (SRMs).

Accomplishments of the Past Year

Edge Detection And Image Analysis Software Developed For Applications In Atom Counting

New image recognition and quantitative image analysis software has been developed for applications in manufacturing at the nanometer scale. This work has immediate applications to quantify feature roughness and asymmetry effects on overlay pattern evaluation used in the feedback and control of lithography stepper tools. This work has also been used in the quantification of algorithm robustness for sample to noise effects. The core concepts from this work will serve as a basis for extensions into atomic scale fabrication of silicon features.

Breakthrough In Low Temperature Atomic Silicon (Si) Surface Preparation

This work is focused on developing atomically flat surfaces that form the basis of substrates for both nanometer scale surface modifications and new metrology methods using the intrinsic crystal lattice. These recent developments helped researchers understand much of the difficulty in obtaining reproducible, atomically flat surfaces using only low temperature, wet processing. The key result is the understanding of a competition between triangular etch pit formation and step and terrace formation.

Breakthrough In Sub-10 Nm Nanofabrication In Silicon

Researchers in the atomic scale manufacturing project made a significant breakthrough in the processing and fabrication of atomically flat and ordered silicon surfaces. The researchers wrote features of critical dimensions as small as 10 nm in silicon. This process has now been repeated several times and can be considered a controlled process. This work is focused on developing the means to reproducibly perform nanometer scale surface modifications and develop new metrology methods for calibration and characterization on the nanometer scale. These recent developments involved the controlled desorption and breaking of hydrogen surface bonds to create stable structures where complex forms and even words can be written in a space of only 100 nm.

First Demonstration Of Interferometric Atom-Spacing Measurements

The atomic scale manufacturing project has successfully measured atom-spacings directly with interferometry. The Ultrahigh Vacuum UHV STM was outfitted with a picometer resolution interferometry system to make the measurements. This is a new application of michelson interferometry using a tunable diode laser to track the measurement as opposed to conventional fringe counting.

FIM Measurements of AFM tips

In collaboration with Purdue University, atomic scale manufacturing project directly imaged AFM tips using a modified Field Ion Microscopy (FIM) approach. This result has not been published elsewhere and is expected to provide a direct method for measuring AFM tips. This result is important in that it is the only known method to give a direct measure of the AFM tip geometry on the nanometer scale

Simulation Of Molecular Forces

Researchers completed an implementation of a simulation environment that improved the resolution of force presentation 4x on each axis. To achieve this result required an emphasis on memory locking, direct molecular force field computation and parallel processing. Various mapping functions were tested to scale down the computed force vectors that ultimately resulted in selection of the logarithm scale to best preserve the weak attractive forces while reducing the very strong repulsive forces.

Virtual environment prototype

An initial prototype virtual environment for controlling an optical trapping (OT) instrument was implemented and initial tests completed. The plans are for the virtual environment to serve as the operational interface for the OT system that is being constructed. A Labview ™ program controls the hardware. The first implementation of this program demonstrates a bi-directional communication capability between the virtual environment and the Labview program. A future implementation will include a monitor positioned next to the ImmersaDesk ™ visualization display that will broadcast live motion pictures of the microscopic view.

Passive Haptic Device With 6 DOF

A prototype six degree of freedom (DOF) passive joystick based on the Stewart platform has been developed and fabricated. The design, based on earlier work done at NIST, will be used to extend the manipulation capabilities of objects within a virtual environment and will assist the user in assembling objects in a more intuitive manner.

Laser Beam Direction Control

Three conceptual prototypes have been built to demonstrate laser beam direction control. One prototype uses traditional piezoelectric tilt platforms to control the scanning angle of a laser beam. The second prototype uses micro-mirror arrays to control the scanning angle of a laser beam and the third uses micro-positioner optics to accomplish the laser angle control.

Visual Capture Of Laser Beam Traces

A high resolution Charge-Coupled Device (CCD) camera is used to image the traces of laser beams under computer control. Flexible image processing programs have been developed, that can capture, filter and process the CCD camera data and locate the laser beam traces. Identification of the size, location and intensity of the traces has been demonstrated.

Micro-Mirror Array Beam Steering

Our researchers invented a novel technique to create a large number of laser beams to grip and manipulate nano-particles. A laser beam is split by a micro-mirror array into a corresponding array of micro-beams that can be steered to different directions independently. With the proper use of reflecting and refracting surfaces this technique has the potential to create optical grippers (cages) that may trap targeted particles.

Micro-Positioner Beam Steering

A novel technique has been invented for the control of the scanning angle of a laser beam. The technique, proposed by our The Johns Hopkins University – Applied Physics Laboratory (JHU-APL) colleagues, requires the scanning of a laser beam at the focal plane of a focusing lens. We demonstrated laser beam scanning with a 1-dimensional micro-positioner. A 2-dimensional fabric of scanning beams can be generated with a MEMS array of our prototype.

RISE Spacecraft Micro-Devices

An informal agreement has been reached with research staff of the JHU-APL to collaborate on the development of advance optical communication systems for their RISE spacecraft. The RISE spacecraft, designed by JHU-APL-SD research staff, has a range of 1000 AU (1 AU = 149,597,870.691 kilometers. As a reference, an Astronomical Unit is the mean distance between the Earth and the Sun and the boundary of the heliosphere is approximately 300 AU) primarily for deep space exploration. The NIST team will be responsible for the design, calibration, control and performance testing of high performance micro-positioners for the needs of the spacecraft.

Small Hazardous Environment Simulator First Phase

Completed construction of the first phase of the small-size hazardous environment simulator. The simulator will create a compact and inexpensive device where hazardous conditions such as, smoke, dust, and humidity can be generated for the purpose of testing sensors and micro-devices that can be used by emergency personnel that will respond to an emergency situation. The simulator was tested with different density smoke generated by varying the composition of the burning fuel.

Microfluidics for Nanodevice Transport

To increase the efficiency of handling nanodevices for testing and assembly, we have constructed working microfluidic arrays for transport of nanocomponents or devices to and from the optical tweezers instrument. This approach substantially reduces the set-up time for working with new samples, and scales naturally to allow both a flow of components to the workspace, and the output of completed devices to the next step in the manufacturing/test process. The production costs of the devices are very inexpensive using both traditional machining techniques and laser-based micromachining.

Robust and Repeatable Manipulation of DNA Molecules

One of the most important applications for nanotechnology products will be the diagnosis and treatment of disease. To address biological applications we are collaborating with CSTL at NIST to optically manipulate individual strands of DNA and control their interaction with protein nanopores. This may lead to more rapid DNA sequencing methods and new techniques for detecting pathogens. We have built a new experimental cell and used it to produce bi-lipid membranes incorporating functional biological nanopores. We have also redesigned the cell to produce new micro-instruments using microfluidics and laser-based micromachining.

Digital Video Microscope and Laser Manipulation Instrument

Optically manipulating small components requires a combination of very high resolution microscopy, video imaging, laser optics and laser beam control. Laboratory are frequently built from expensive and inflexible commercial microscopes. We have built a compact and cost effective microscope for optical manipulation. The instrument includes a fiber optic laser beam input for portability and increased range of applications, and digital video imaging for fast image-based control of trapped components. The instrument is currently being used to optimize membrane growth for the DNA manipulation experiments.

New Laboratory

A new laboratory has been built for optical testing and assembly of nano and micro devices. The laboratory was selected and completely refurbished to house the optical trapping instrument and related developments in optical scanning, microfluidic delivery systems, imaging, and computing support. The laboratory was completed in FY2002, and has already provided facilities to several students, guests, and NIST staff.

Workshops

Session Chair (two sessions): SPIE 2002, NIST Gaithersburg, MD, October 2001

Poster presentation: MEMS Alliance workshop held at Johns Hopkins Applied Physics Laboratory, Laurel, MD, November 2001

NIST MEL Booth: Defense Manufacturing Conference, Las Vegas, NV, December 2001

Invited Presentation: NSF- European Commission (EC) Nanomanufacturing and Processing Workshop, San Juan, Puerto Rico, January 2002

Presentation: Finland research study group, Micro-production technologies, NIST Gaithersburg, February 2002

Conference Co-chair, Presenter: SPIE Microlithography, Santa Clara, CA, March 2002

Presenter: OMAG Metrology workshop, Austin, TX, June 2002

Session Chair, Presenter: World Automation Congress WAC ISORA 2002 conference (9th International Symposium on Robotics and Applications), Meso-Micro-Nano Robotic Systems and Applications," Orlando, Florida, June 9-13, 2002

Invited Presentation: European Commission / National Science Foundation (EC/NSF) Workshop, Instrumentation and measurement systems for nanotechnologies, Grenoble, France, June 2002 http://www.nsf.gov/od/lpa/news/press/01/pr0197.htm

Invited Presentation: Ministry of Research, National Nanotechnology Initiative team, Paris, France, June 2002

Poster presentation: NIST Nanotechnology Open House, Gaithersburg, MD June 2002

Presenter: SEMATECH Metrology workshop November 2002

Special sessions on In2m for the IRVS/ ISR:

Special sessions on Integrated Nano-to-Millimeter Manufacturing Technologies topics will be held at the 2003 International Robots and Vision Conference/Expo (IRVS) and the 34th International Symposium on Robotics (ISR). The following topics will be highlighted: 1) Construction robots and related devices, 2) Homeland defense robots and related devices, 3) Micro-assembly robots and related devices, 4) Medical robots and related devices, 5) Ladar sensors as an alternative to vision devices, and 6) Nano-technology. Working with the committee, we will recruit experts from NIST and other organizations to give tutorial type presentations that will introduce these new technologies to the thousands of industry people who normally attend these events.

Other Information

Joint Defense ManTech Panel (JDMTP) Electronics Processing and Fabrication (EP&F) Subpanel

One of the program members serves as a liaison for NIST on the JDMTP EP&F Subpanel. Representatives from the Army, Navy, Air Force, DLA, Department of Energy Sandia National Laboratory, NIST, and two industry groups comprise the sub-panel.

National Science Foundation (NSF) Meeting

A member of this program participated in a National Science Foundation (NSF) meeting to propose recommendations to the Nanotechnology Executive Committee on defining grand challenges in manufacturing at the nanoscale. At the meeting an overview of NIST activities in nano-technologies was presented.

NSF Proposal Review Panel

During March 2002, a member of this program served on the NSF review panel for proposal on Nano-technologies.

Standards Participation

Wafer Preparation Standards

NIST is working with International SEMATECH to develop wafer standards that are appropriate for calibrating today's high-resolution imaging tools. This effort leverages MEL's current fabrication and measurement methods and procedures under development through the Integrated Nano-to-Millimeter Manufacturing Technologies Program (and its predecessor the Nanomanufacturing Program).

SPM Error Source Definition

Error sources and characterization techniques affect the accuracy and repeatability of nanoscale measurement and manipulation operations performed by scanning probe microscopes (SPMs). During FY2003, we will initiate work on a prototype standard in collaboration with the staff of the Atom-scale Measurement and Lithography project to enumerate those error sources and characterization techniques. Preliminary image analysis will be used to identify and make a quantitative assessment of the errors present. These results will be augmented with a thorough literature search to establish a projected baseline of error sources, models and the required characterization techniques. When sufficient progress is achieved the work will be provided to appropriate standards groups for consideration in developing a new standard in this area or an addition to an existing standard.

Intelligent Control of Mobility Systems

Program Manager: Maris Juberts	
FTEs:	14.0
Program Funding	$4.3 M

FY2003 Projects:

- Industrial Autonomous Vehicle (IAV)
- Army Research Lab (ARL) Support and NIST Vehicle Testbed
- PerceptOR
- Future Combat System (FCS)
- Department of Transportation (DOT) Metrics – Road Departure Warning Systems

Program Goal

By 2005, provide architectures and interface standards, performance test methods and data, and infrastructure technology needed by the U.S. manufacturing industry and government agencies in developing and applying intelligent control technology to mobility systems to reduce cost, improve safety, and save lives. This program concentrates its efforts in the following three areas:

Industrial Material Handling & Other Industrial Applications

reduce costs and improve efficiency in industrial material handling by providing to the industrial autonomous guided vehicle (AGV) industry performance tests to support the use of non-contact safety sensors and appropriate control systems architectures and standards to enable the use of advanced navigation techniques based on such non-contact sensors;

Department of Defense (DOD) Unmanned Ground Vehicles

save lives and improve national defense capabilities by providing agencies of the Department of Defense (DOD) with the control system architectures, advanced sensor systems, research services, and standards to achieve autonomous mobility for unmanned ground vehicles (UGV); and

Performance Measures for Mobile Robots:

improve vehicle safety, transportation system capacity, and accelerate advancement of mobile robots through the deployment of advanced sensors and intelligent vehicle control systems on manned and unmanned vehicles by providing performance metrics (i.e., objective evaluation and measurement methods, testing procedures, and standard reference data) needed to analyze sensor and control system effectiveness.

Customer Needs

To develop and use intelligent mobile systems, industry and government agencies need architectures and interface standards to ensure interoperability, real-time sensing and measurement for control systems, and metrics for evaluating performance of components and systems. The program addresses material handling needs in discrete part manufacturing as identified in the Integrated Manufacturing

Technology Roadmap (IMTR). Customers require material handling systems that can be changed to meet any handling and movement requirement without the need for redesign and manual rearrangement, as well as material handling control systems that can seamlessly integrate with multiple complex handling systems and self-adapt to changes in handling system configuration or processing requirements.

In addition, advanced mobile robot technology is needed in manufacturing enterprises for plant physical security, hazard detection, inventory control, and cleaning. These needs also apply to other industries such as agriculture, construction, postal service and service robots. These needs have been expressed by industry representatives at workshops, conferences and through personal contact/meetings with NIST personnel.

As an example of the need for architectures and interface standards, the DOD initiated plans for the deployment of robotic vehicle platforms in the battlefield and plans to standardize the architecture and interfaces. This will encourage the use of commercially available "plug-and-play" components and provide reusability and interoperability on a variety of ground vehicles.

In the area of performance metrics, companies developing advanced component and system technologies and government users of such technologies need measures of performance for evaluating and specifying technology elements, products, and intelligent behaviors of complete systems. Such performance metrics improve the efficiency of development efforts, provide the basis for an equitable and competitive marketplace, and provide the basis of legal and regulatory decisions.

As an example of the need for performance metrics, the Department of Transportation (DOT) Intelligent Transportation Systems (ITS) is working to evolutionize the U.S. transportation system by including advanced sensors, information technology, communication, and safety systems, however, they need a way to evaluate the performance of this advanced technology for its program. The National Highway Traffic Safety Administration (NHTSA) recognized that it would be useful to have methods to develop a real-time measurement and roadway calibration system to evaluate effectiveness of on-vehicle crash avoidance systems for highways. The DOD Demo III program relies on NIST-developed methods to evaluate the performance of advanced sensors, algorithms for obstacle detection and avoidance, autonomous mission/task planners, and the ability of robotic systems to execute military tactical behaviors effectively and intelligently.

Technical Approach

Robotics industry leaders point out that advances in military, transportation, medical, and other non-manufacturing robotics applications, where research and development investments are justified by dramatic potential benefits, will provide the technologies to advance future generations of robots for application in manufacturing. Industrial robots will trail in technology development, adopting advanced technology as it is proven to be reliable and cost effective; autonomous mobile systems for military applications represent the forefront of robotics research.

Thus, to achieve the program objectives, the primary technical approach is to use the NIST Real-time Control System (RCS) architecture as an example of an open system architecture for building complex autonomous robotic systems for other government agency programs (e.g., military, transportation) and funds, and then invest direct appropriations to transfer relevant advanced robotic technology to industrial applications.

The RCS architecture provides a systematic analysis, design, architectural framework, and implementation methodology for developing real-time sensor-based control systems. Functional task execution is viewed hierarchically with motor skill functions, like steering and speed control, performed at lower levels and coordinated actions between vehicles performed at higher levels. The control system uses sensory information to guide the intelligent vehicle in the execution of complex tasks. Planning for task execution and for adaptation to changes in the environment are also parts of the total hierarchy.

Program Objectives and Technical Outputs

Industrial Material Handling

Objective 1:

By 2005, provide industries with the necessary standards, performance metrics, and infrastructure technology to support the use of non-contact safety sensors and control system architectures that enable broader use of advanced perception and navigation techniques in the AGV, and other industries.

Objective 1a:

By FY2005, support relevant voluntary standards.

Technical Outputs

FY2003:
Performance tests for safety sensors.

FY2004:
NIST Internal Report (NISTIR) describing the use of ladar and sonar sensors for safety and advanced navigation.

FY2005:
Proposal for a standard AGV system architecture to allow interoperability of components and systems.

Objective1b:

By FY2005, work with key industry and user partners to advance the state of autonomous robotic technology.

Technical Outputs

FY2003:
Demonstration of DOD UGV technology on the Intelligent Autonomous Vehicle (IAV) project platform at NIST.

FY2004:
Demonstration of Internet-based control.

FY2005:
Demonstration of advanced navigation with industry partner.

DOD Unmanned Ground Vehicles

Objective 2:

By 2005, provide DOD agencies with the control systems architectures, advanced sensor systems, research services, and standards to achieve next generation autonomous mobility for unmanned ground vehicles.

Objective 2a:

By FY2005, support the Army Research Laboratory (ARL) Demo III program and subsequent programs.

Technical Outputs

FY2003:
UGV Technology Readiness Level (TRL) assessed for autonomous mobility in accordance with Demo III and Future Combat System (FCS) program requirements.

FY2004:
Next generation perception, learning and multi-vehicle tactical behaviors implemented.

FY2005:
Field Operational tests for UGV intelligent behaviors available.

Objective 2b:

By FY2005, implement, maintain and demonstrate NIST mobility testbed vehicle.

Technical Outputs

FY2003:
Performance tests for sensors, processors, and intelligent vehicle control system elements for autonomous cross-country navigation conducted.

FY2004:
Conduct of experiments to evaluate and refine next generation perception, learning, and multi-vehicle tactical behaviors.

FY2005:
Demonstration of next generation autonomous technology and tactical behaviors at NIST.

Objective 2c:

By FY2005, support relevant military standards activities.

Technical Outputs

FY2003:
Support acceptance of 4-dimensional (4D)/RCS Demo III control system architecture as a reference standard for the Joint Architecture for Unmanned Systems (JAUS), Vetronics and Weapon Systems Technical Architecture Working Group (WSTAWG) military standards.

FY2004:
Performance/conformance tests for sensors, perception algorithms, vehicle path planning, cross-country navigation and intelligent tactical behaviors conducted.

FY2005:
Standards work for deployment of UGVs in the battlefield.

Objective 2d:

By FY2005, support the Defense Advanced Research Projects Agency (DARPA) sponsored Future Combat System Program

Technical Outputs

FY2003:
Autonomous vehicle navigation subsystem designed for Boeing in support of Phase II of the Army/DARPA FCS program.

FY2005:
Core technology, infrastructure technology, and testing services delivered in support of the follow-on phase contracts to the FCS teams.

Performance Measures for Mobile Robots

Objective 3:

By 2005, provide the evaluation and measurement methods, testing procedures and standard reference data needed for performance analysis and deployment of advanced sensors, and intelligent vehicle control systems on manned and unmanned vehicles used in next generation transportation safety systems and in UGVs for the military.

Objective 3a:

By FY2005, support relevant standards activities in Intelligent Transportation Systems (ITS).

Technical Outputs

FY2003:
Performance tests for Road Departure Warning Systems (RDWS) conducted.

FY2004:
NISTIR describing the use of advanced sensors and data collection systems to evaluate next generation vehicle safety systems on roads published.

FY2005:
Performance measurement methods transferred to mobile industrial material handling systems and military transportation systems.

Objective 3b:

By FY2005, support the National Highway Traffic Safety Administration (NHTSA) Intelligent Vehicle Initiative (IVI) program.

Technical Outputs

FY2003:
Effectiveness of measurement methods used by industry team for conducting the NHTSA-sponsored Field Operational Test on vision-based RDWS evaluated.

FY2004:
Report on analysis of Field Operations Test (FOT) test data for RDWS.

FY2005:
Refined measurement methods and test procedures based on industry feedback.

Objective 3c:

By FY2005, develop measurement methods and test procedures to generate documented, defendable data to establish the TRL for the autonomous mobility subsystem for FCS concept of operations.

Technical Outputs

FY2003:
TRL-6 tests using the Demo III experimental unmanned vehicle (XUV) vehicle on three types of relevant terrain for operations of FCS equipped forces developed and conducted.

FY2005:
Development of core technology, measurement technology, and testing methods in support of the follow on phases of the TRL experiments.

The robotic HMMWV takes its orders from the NIST Real time control System

Anticipated Impacts

We anticipate that the research from this program will have the following positive impacts: lives saved and throughput improved on U.S. roads due to deployment of intelligent vehicle crash avoidance technology by the transportation industry; UGVs will replace soldiers in hazardous military operations, improve outcome of battle experiments and operations, and reduce operating costs; an expansion of AGV and other industrial robot markets because of improved performance and lower costs for building and using intelligent mobile robots; more flexible material handling systems.

Accomplishments of the Past Year

Unmanned Ground Vehicles

Successful ARL Demo III UGV Experiment at Fort Indiantown Gap, PA – November 2001

NIST helped develop the mobility controller for the experimental UGVs used in the experiments. The Demo III XUV successfully navigated many kilometers of difficult off-road terrain with only high-level mission commands provided by an operator from a remote location.

DARPA, ARMY Future Combat Systems program Lead System Integrator Specifies 4D/RCS

DARPA and the Army on March 2, 2002 announced the selection of the team of the Boeing Co. (Anaheim, Calif., and Seattle, Wash.) and Science Applications International Corp. (SAIC) as the Lead Systems Integrator (LSI) for the concept and technology development phase (Phase II) of the FCS program. Boeing's Broad Industry Announcements in the area of unmanned ground vehicles call for "software controls/processing consistent with the 4D/RCS architecture."

RCS Controlled Robotic Vehicle Demonstrated for the Secretary of the Army

The Demo III team including the ARL, General Dynamics Robot Systems (GDRS), and NIST demonstrated an XUV for Secretary White on May 30, 2002. The XUV was controlled by an implementation of RCS that was co-developed by NIST and GDRS.

RCS Controlled Robotic Vehicle Demonstrated for Homeland Security Team

The Demo III team including the ARL, GDRS, and NIST demonstrated an XUV for 4-star General (Ret) Barry R McCaffrey, the Olin Distinguished Professor of National Security Studies for the U.S. Military Academy on August 23, 2002 at Aberdeen Proving Ground, MD. The XUV was controlled by an implementation of RCS that was co-developed by NIST and GDRS.

"4D/RCS: A Reference Model Architecture for Unmanned Vehicle Systems" Published

This document, published as a NIST Internal Report (NISTIR), provides a comprehensive description of 4D/RCS and presents engineering guidelines for implementation of systems based on this architecture. This publication marks a major milestone in documenting the latest version of the architecture for the autonomous vehicle systems community, and it will be distributed to standards efforts and collaborators to help promote a broader understanding of 4D/RCS.

Winners of BAA Solicitation on Next Generation Ladar for Unmanned Ground Vehicles Announced

Four contracts for the design of Next Generation Ladar for driving UGVs in military applications were awarded. A variety of different technical approaches were selected including some of the most advanced approaches that are available. The awards are for the design of an Engineering prototype to advance the Ladar range imaging component/subsystem technologies to meet the needs for UGVs.

Ladar Calibration Scheme Developed and Applied

A ladar (laser ranger imager) calibration scheme was developed and used to calibrate each of the ladar sensor in the Demo III vehicle. The control system for the vehicle uses ladar technology to build a model of the world that is geometrically accurate to a resolution that is sufficient for autonomous driving. The accuracy of the maps, or models, is dependent upon the system knowing precisely what laser beam angles emanate from the ladar. Inaccurate angles result in a fuzzy 3-dimensional dimensional model.

Industrial Material Handling & Other Industrial Applications

Industrial Autonomous Vehicle Project Makes Progress

We developed an indoor, mobile testbed, called NIST-IR (NIST Industrial Robot) that has a mobile robot base which supports a camera used to acquire information from colored tape lines and unique patterns installed in hallways and a LADAR sensor used for obstacle detection and robot docking. The unit successfully performed a vehicle lane- and pattern-following demonstration. We produced a video of the demonstration for distribution to interested industry, academia, and government vehicle developers and users.

The experiments with the testbed vehicle show the industry how advanced perception sensors can be used on AGVs to improve non-contact bumpers, allow vehicles to move faster, detect objects and people faster, and provide real-time 3D mapping capabilities

Performance Measures for Mobile Robots

DOT Metrics Project Makes Progress

The first draft of acceptance tests for Phase I of the RDWS FOT Objective Test Procedures were developed and delivered to NHTSA.

Designed and developed a performance test to measure error of Inertial Measurement Unit/Global Positioning System (IMU/GPS) navigation sensor system measurements while the system is driven on a vehicle at high speed. The performance tests on our vehicle showed that the estimated error in vehicle position deviated not more than 2 cm from known reference points.

Plans for open-road sensor characterization tests, which are part of the FOT objective test procedures, were developed and will be implemented in 2003.

Workshops

AGV Workshop Planned

In FY2003, we will hold a workshop for AGV users, mobile robot and sensor researchers. The workshop will ask the users how they would focus NIST mobile robot research in standards, measurements, and advanced technology to provide the largest impact to them and their industry.

Standards Participation

- American Society of Mechanical Engineering (ASME) B56.5 AGV Bumper Standards Committee - We are lending our expertise concerning the use of LADAR sensors in non-contact safety systems.
- ISO Technical Committee 204, Working Group 14 – Standards for Lane Departure Warning Systems – participant
- DOD Joint Architecture for Unmanned Systems – participant
- DOD Weapon System Technical Architecture Working Group – participant
- Vehicle Electronics Standards – participant

Program Manager:
Fred Proctor

FTEs:	10
Program Funding:	$1.5 M

FY2003 Projects

- STEP-NC machining and inspection validation
- Metrology Interoperability
- Robot Communication and Information

Intelligent Open Architecture Control

Program Goal

By 2005, develop and validate key interface standards, and conformance tests for those standards, to achieve interoperability among control systems for machines on the factory floor, and between these systems and design and planning systems, as well as factory data networks.

Customer Needs

Over the past two decades, information technology has dramatically increased the intelligence of the upper levels of manufacturing systems. In the next 20 years, this intelligence will reach down to the factory floor as individual machines become much smarter, more easily integrated, and able to communicate more broadly, predict results and avoid or diagnose mistakes, use extensive in-process gaging, and use scientific models to optimize productivity.

These trends, echoed in the Integrated Manufacturing Technology Roadmap (IMTR, now known as the Integrated Manufacturing Technology Initiative [IMTI]), have great potential to decrease time and cost to market, improve quality, and increase productivity. However, they require a seamless flow of information and total integration throughout the enterprise, and today, in the words of one industry workshop attendee, "all the links are broken."

How much is the current lack of interoperability costing U.S. robotics industry? Taking industrial robots as an example, the total installed system cost is typically three to five times the cost of the robot itself.[1] In a $1 billion U.S. robot market (1999), this equates to $2 billion to $4 billion in added system costs. Software integration accounts for at least 25 percent of the total installed system cost. Much of that cost (up to 50 percent) could be reduced through the development and use of standardized open architecture controllers. The potential savings would be $250 million to $500 million per year. A look at cell integration costs in the aerospace industry paints a picture of comparable potential savings: $10 million of capital equipment takes 100 person-years to integrate.[2]

[1] Data presented by Robotics Industry Forum, 1999

[2] Boeing data

Technical Approach

Open architecture control, a common architecture of system components and interfaces, is the key to connecting control, design and planning, and factory data systems and to realizing the benefits of increased intelligence in manufacturing processes.

The IOAC program approach is to realize interoperability by facilitating and participating in industry efforts to standardize open architecture control. Interoperability requires three steps:

- vendor agreement to a common architecture that defines system components and their relationships,
- development and implementation of valid interface specifications, and
- establishment of conformance tests for determining whether products faithfully implement the specifications and achieve plug-and-play operation.

The program is involved in each of these steps. Program staff hold workshops, in collaboration with industry and government agencies, to identify the most pressing interoperability problems; facilitate and participate in industry efforts to develop suitable architectures as a basis for interface specifications; establish testbeds with real manufacturing equipment to implement and test candidate specifications; And, in cases where conformance tests are needed to ensure interoperability, work with industry members to develop them.

Currently, the program staff is working closely with industry groups to achieve cross-cutting benefits. These groups include the Automotive Industry Action Group (AIAG), Robotic Industries Association (RIA), and Open Modular Architecture Controller (OMAC) Users Group.

Through AIAG and OMAC, the program members are working on standards to integrate design, process planning, machining and inspection so that design intent (such as features and their tolerances) can be conveyed throughout these processes.

Through RIA, program staff members are working on standard data representations for robot controller configuration, operation and maintenance information, leveraging Internet standards such as Ethernet, Transmission Control Protocol/ Internet Protocol (TCP/IP) and File Transfer Protocol (FTP).

Program Objectives and Technical Outputs

Objective 1:

By FY2003, validate standards for data interoperability for machining, robotics and metrology equipment.

Technical Outputs

FY2003:
Interoperability demonstration of STEP-NC (STandard for the Exchange of Product model data – Numerical Control) for milling.

FY2003:
Testing utilities for the I++ dimensional measuring equipment (DME) interface.

FY2003:
OMAC API (Application Programming Interface) General Motion Control reference implementation.

FY2003:
Database implementation of American Welding Society welding procedures and test results.

FY2003:
RIA Technical Report (TR) on robot controller network configuration.

Objective 2:

By FY2005, provide conformance tests for standards for data interoperability for machining and metrology equipment.

Technical Outputs

FY2003:
Conformance tests for the I++ DME interface.

FY2004:
STEP-NC pilot testing report on conformance tests for computer numerical control (CNC) machine tools.

FY2005:
STEP-NC conformance tests for computer-aided manufacturing (CAM) and CNC.

Anticipated Outcomes

The program is expected to accelerate the implementation and commercial availability of controllers with advanced capabilities, and to reduce controller life cycle costs due to easier integration of controller components and increased competition among controller component vendors. This will benefit U.S. controller vendors and users differentially by helping them to gain a competitive advantage in implementing and applying advanced capabilities at lower costs.

Open architecture standards enable seamless electronic data transfer between design and manufacturing

Accomplishments of the Past Year

RIA Technical Report on Robot Controller Data Requirements Completed

The report, RIA TR 15.04-1 on Robot Controller Data Requirements, was balloted in October 2002. The report identifies existing standards to be used by robot controllers (Ethernet, TCP/IP, and FTP) and describes information to be supplied by robot controller vendors to aid in program upload, download, and compare for configuration and recovery.

OMAC Application Programming Interface (API) Specification Revised

This revision incorporates results from packaging motion tests in the general motion control testbed.

Robotic Welding XML Data Definitions Published

The XML (Extensible Markup Language) data definition for robotic welding allows welding configuration information to be shared electronically, easing the integration of robotic welding equipment with robots.

Dimensional Measuring Equipment Interface Testing Tools Published

Software test suites were written for the I++ (Integrated Inspection) standard for data exchange between metrology equipment and programming and analysis software. The software test suites were provided to the I++ testing team, which includes vendors such as Brown and Sharpe, LP Metrology, and Zeiss. I++ is a working group of five automotive manufacturers that have joined together to address the problem of lack of compatibility between metrology systems.

STEP-NC CAM conformance testing pilot completed

Using software from STEP Tools, Inc. and VulcanCraft, a pilot project demonstrated the virtual machining of sample parts using STEP-NC (ISO 10303 AP 238), virtual machining and automated feature recognition.

Standards Participation

- ISO Technical Committee (TC)184/Sub-committee (SC)4, Industrial automation systems and integration/Industrial Data, for ISO 10303 AP 238, the STEP-NC Application Interpreted Model
- ISO TC 184/SC1/Working Group (WG)7, Industrial automation systems and integration/ Physical device control/Data modeling for integration of physical devices for ISO 14649, the STEP-NC Application Reference Model
- RIA R15.04, for robot controller communication and information
- American Welding Society (AWS) A9, for Computerization of Welding Information
- CAM-I (Consortium for Advanced Manufacturing - International) subcommittee of DMIS (Dimensional Measuring Interface Standard) National Committee

Program Manager:
Charles J Fronczek Jr.

FTEs	1.9
Program Funding:	$501 K

FY2003 Projects

- Artifact Development for 3D Systems
- ATEP_CMS Chebyshev Refernce Algorithms
- Dimensional Measurements in Large Scale Metrology Standards
- Displacement Measurements for Laser Tracker Uncertainty Estimates
- Large Scale Artifact Calibration
- Laser Tracker Point Coordinate Uncertainties

Large Scale Metrology

Program Goal

By FY2007, provide U.S. large-scale-manufacturing metrologists with the tools (standards, artifacts, and methodologies) for characterizing instruments to reduce calibration time by 50 percent, reduce intervals between calibrations by 50 percent, and establish traceability, thereby creating an effective savings of $60 million directly and $600 million indirectly.

Customer Needs

The Large-Scale Coordinate Metrology program supports measurements and measurement research on the scale of one meter or larger and focuses on problems affecting coordinate metrology in three areas of interest: standards, task-specific measurement uncertainty, and machine tool metrology. As such, we provide a neutral resource for manufacturers and users of large scale measuring instruments. In particular, the program develops virtual artifacts and methodologies for evaluating coordinate measurement systems (CMSs). These artifacts and methodologies enhance calibrations, evaluate system performance, allow intercomparisons, and estimate task-specific measurement uncertainty. This, in turn, allows customers in the manufacturing community to obtain measurements with valid uncertainty statements so that they can make sound economic decisions to accept or reject workpieces.

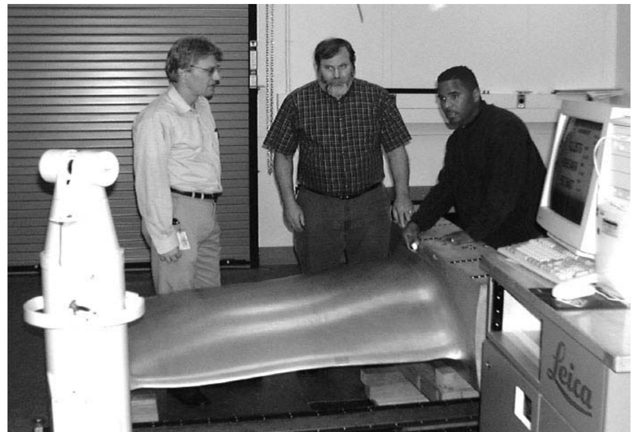
Recent advances in CMSs have created a need for new ways of determining the uncertainty of measurements. Traditional coordinate measuring machines (CMMs) produce output in the form of discrete point coordinates. On the near horizon are CMSs based on photogrammetric principles and "structured light systems" that collect dense clouds of data, and the output is used to extract characteristics of large, complex free-form surfaces. Conventional artifacts are not sufficient to evaluate the performance of these instruments. In addition, in some cases, up to half of the total measurement uncertainty is attributable to the inaccuracy of the software used to fit raw measurement results (sets of x, y, and z) to geometric representations of the artifact being measured. CMS users and vendors seek objective analysis methods, analysis tools, and a neutral test service to assess the uncertainty associated with this type of software.

The lack of CMS hardware and software testing ability could lead to a company's inability to defend uncertainty estimates during, for instance, an ISO audit. The lack of measurement traceability could lead to isolation of a U.S. industry sector from the world market place.

Users such as Boeing, the Propulsor Group of the Naval Surface Warfare Center (NSWC), the Large Millimeter Telescope group (LMT), and equipment manufacturers such as Automated Precision Inc, Dimensional Photonics, and Imetric SA have expressed, both orally and in writing, a need for research into standards in this area.

Technical Approach

The Large Scale Coordinate Metrology program, while maintaining expertise in the traditional form of CMSs, is preparing to deal with emerging types of software and hardware through research into the needs associated with the new class of instruments. Standards issues are being addressed through the development of national, international, and Department of Defense (DOD) standard specifications for coordinate metrology instruments. In addition, research is being focused on performance issues and subsequent artifact development in support of these standardization efforts. Staff of the Large-Scale Metrology program are actively involved in both the American National Standards Institute (ANSI) and ISO standards development efforts in the area of performance assessment of large-scale coordinate metrology instruments. The leadership as well as support roles taken on by NIST staff within these bodies will ensure that U.S. manufacturing needs are addressed and met. This interagency effort also will help to unify and harmonize national and international CMS standards. Additionally, NIST is leading a DOD effort to create an inter-service military CMM performance standard.



Large Scale Coordinate Metrology Group members discuss methods to measure complex geometries.

In addition to the standards work, program staff will conduct research to better quantify the sources of CMS errors. Our research and development efforts are primarily focused on measurement processes performed in situ, as opposed to those performed in a national or a primary calibration laboratory. Three types of processes are being explored: coordinate metrology with linear-axis CMMs; coordinate metrology using optically based CMSs (theodolites systems, tracking laser interferometer systems, or laser ranging systems); and in-process machine metrology for emerging manufacturing technologies. NIST plans to develop enhanced performance evaluation techniques and artifacts that will lead to more thorough instrument characterization and more advanced methods for error elimination. For example, one current focus area is virtual instruments, or software that uses instrument performance information to develop more accurate task-specific measurement uncertainty estimates through realistic measurement modeling and simulation. As part of this program, we developed a facility, the Large Scale Metrology Calibration and Research Laboratory, that will enable high accuracy calibrations and measurements.

Program Objectives and Technical Outputs

Objective 1

By FY2005, produce report detailing measurement procedures, test methodologies and data analysis techniques for performance evaluation and point coordinate measurement uncertainty estimation of laser tracker coordinate measuring systems to assist U.S. manufacturing metrologists in assessing the performance of laser tracker coordinate measuring systems.

Technical Outputs

FY2003:
A report on the investigation into the use of displacement measurement methods for laser tracker performance evaluation and point coordinate measurement uncertainty estimation.

FY2003:
A report detailing current methodologies for assessing laser tracker point coordinate measurement uncertainty.

FY2004:
A report comparing current industrial practices for assessing point-coordinate measurement uncertainty and the proposed new methodologies.

FY2005:
Published report detailing measurement procedures, test methodologies and data analysis techniques for performance evaluation and point coordinate measurement uncertainty of laser tracker coordinate measuring systems.

Objective 2:

By FY2007, produce an artifact for performance evaluation and interim testing of large scale 3-dimensional scanning, structured light and non-contact coordinate measuring systems to assist U.S. manufacturing metrologists.

Technical Outputs

FY2003:
A report of the findings of an investigation into the attributes of a single artifact that will satisfy the particular measurement needs of multi-technology optical coordinate 3-dimensional measuring systems users.

FY2004:
A proposed artifact design circulated to users and manufacturers of large-scale coordinate measurement systems to obtain information for design review and or measurement plan modification.

FY2005:
A drawing and technical specifications produced for fabrication of the large-scale performance coordinate measuring system evaluation and interim testing artifact.

FY2006:
An artifact delivered to a select group of Navy users for final design review and measurement plan assessment.

FY2007:
A report detailing measurement procedures test methodologies, and data analysis techniques for use with the large-scale performance evaluation and interim test artifact.

Objective 3:

By FY2006, provide an Internet based test service for Algorithm Testing and Evaluation of Coordinate Measuring Systems (ATE-CMS) to assist manufacturers in characterizing an often-ignored source of uncertainty.

Technical Outputs

FY2003:
The ATE-CMS Chebyshev reference algorithms implemented to generate a web- based battery of reference pairs for use by industry for self-assessment. The capability of our general, rigid surface reference fitting algorithms for variously defined complex surfaces extended. A web-based wide array of reference triples, datasets, and reference fits created for use by industry for self-assessment.

FY2004:
Reference algorithms developed for and problems investigated in handling massive quantities of measured data including the following issues: filtering, the relationship between traceability and outlier removal, and the application of signal and image processing techniques to large data sets.

FY2004:
An investigative report on the quantification of the effects of using high order mathematical interpolation to compare results of different measurement methods.

FY2005:
A web-based resource for industrial use covering large data sets with reference results including the use of data handling techniques to lower uncertainties of measurement by taking advantage of massive over-sampling developed.

FY2006:
Simulation methods developed for evaluating task-specific measurement uncertainty and investigate development of a software tool to test such software.

Interactions

The program is expecting active partners in NIST's Information Technology Laboratory in statistics for uncertainty estimates, NIST's Building and Fire Research Laboratory in the areas of laser distance and ranging (LADAR) calibration, in government agencies through the NSWC, the Large Millimeter Telescope Program, and in private industry through Boeing, Automated Precision Inc., and Dimensional Photonics. The ATE-CMS test service is unique worldwide, although another national measurement institute PTB (Physikalisch-Technische Bundesanstalt, Germany) has a limited service.

Accomplishments of the Past Year

- Implemented an advanced metrology system in the ship repair and production facility at the Atlantic Marine Holding Company (AMHC) in Mobile, AL.
- Wrote U.S. responses to the following ISO Draft International Standards:

  Optics and optical instruments — Field procedures for testing geodetic and surveying instruments — Part 5: Electronic tacheometers

  Optics and optical instruments — Field procedures for testing geodetic and surveying instruments — Part 6: Rotating Lasers and the Committee Draft

  Optics and optical instruments — Field procedures for testing geodetic and surveying instruments — Part 7: Optical Plumbing Instruments

- Published a technical paper that included details of the underlying reference algorithms for ATE, their technical approach, verification testing, and associated user documentation and reference pairs available for download on the World Wide Web.
- Wrote a detailed manual of standardized calibration procedures for DOD CMMs.
- Published paper, "A Standardized Laser Tracker Calibration System," and presented it to the 2002 Measurement Science Conference.
- Published and presented keynote paper on state of the art in large scale metrology for the International Organization for Production Engineering Research (CIRP) conference.
- Edited version of the American Society of Mechanical Engineers (ASME) Optical Coordinate Measuring Systems - Laser Tracker Standard.
- Procured parts for an initial design of a test artifact for evaluating instruments that acquire data by massive sampling and whose output is in the form of shape parameters and primitive geometries.
- Created reference data set pairs for least-squares fitting algorithms, and documentation and reference pairs readied for download to the World Wide Web.
- Contributed to publication of the final standard by continued work in the standards project team of ASME B89.4.10 (Dimensional Metrology, CMM Software Evaluation).
- Completed the ISO 10360-6 (Geometrical Product Specifications — Acceptance and reverification tests for CMM/ Estimation of errors in computing Gaussian associated features) through continued work in ISO TC 213 WG 10.

Anticipated Impacts

By FY2003, we expect that the adoption and promulgation of a performance standard for laser trackers will allow American manufacturers unhindered access to the European marketplace.

By FY2005, we expect to produce a document that will advance the knowledge of uncertainty statements for laser trackers thus allowing the U.S. manufacturers expanded global presence.

By FY2007, we expect that an international consensus on CMS performance testing for a new class of instruments – both in the hardware and software arenas – will help to validate this class of instruments in the coordinate metrology arena.

Standards Participation

ASME B89 Division 1 Length

- Project Team 1.7 Measuring Tapes Project Team 1.7 Measuring Tapes

ASME B89 Division 4 Coordinate Measuring Technology

- Project Team 4.7 Ball Bar Systems,
- Project Team 4.11 Probes and Probe Changers,
- Project Team 4.13 Interim Testing of CMMs,
- Project Team 4.14 Non-contact Scanning Probes,
- Project Team 4.19 Optical Coordinate Measurement Systems,
- Project Team 4.20 Artifacts Uncertainty,
- Project Team 4.21 CMM Performance in Realistic Environments,
- Project Team 4.22 Portable CMMs,

ISO Technical Committee (TC) 213 – Dimensional And Geometrical Product Specification And Verifications

- Working Group 4 Uncertainty of measurement and decision rules, and
- Working Group 10 Coordinate measuring machines

U.S. Technical Advisory Group ISO TC 172 Optics and optical instruments.

- Subcommittee 6 Surveying Instruments

Measurement Services

Special Length Calibration Services:

- 10030C Surveying and Oil Gaging Tapes
- 10040S Special Test of Surveying Level Rods
- Special Measurement of Ball Bars

Program Manager
Al Jones

FTEs:	10
Program Funding:	$1.6 M

FY2003 Projects

- Environment to enable self-integration
- A Web-based, distributed, testing and demonstration environment

MANUFACTURING ENTERPRISE INTEGRATION

Program Goal

By 2005, demonstrate the potential for reducing the cost of Business-to-Business (B2B) software integration through new types of semantics-based measurements, standards, and infrastructural technologies that enable the building and testing of self-integratable software applications.

Customer Need

As manufacturing enterprises implement new business structures, they are making the Internet a critical part of their business strategy. The Internet makes it possible for manufacturers to actually link up with their partners, suppliers, and customers. However, the Internet is not enough. To turn possibility into reality requires automatic integration of a myriad of enterprise-level software applications. Several market analysts, including Gartner and D.H Brown, project that the market for these applications will reach $100 billion by the year 2005. They also estimate the integration costs to range from two to five times the software costs.

The current approach to software integration is to decompose the integration process into two parts: communication protocols and interface specifications. Communication protocols govern the physical exchange of bits and bytes between the computers on which the software applications execute. There are many national and international standards for these protocols, and these standards can now be implemented in computer hardware and system software that is separate from the manufacturing applications. Interface specifications govern the syntax and semantics of every piece of information exchanged by those applications. For any particular specification, there may be none, one, or many standards. The availability of such standards has the potential to reduce the number of required translators from O(N2) to O(N) — where O(.) means “on the order of”, and N is the number of computers.

The benefits from the communication standards that govern Internet and network communications have largely been realized. Bits and bytes can be sent cheaply, quickly, securely, and accurately, from one computer to another anywhere in world. Unfortunately, similar benefits have not accrued from standardizing interface specifications for information exchanges. The development, testing, and implementation cycle for these specifications can take years. Furthermore, since numerous organizations and consortia develop them, multiple, even conflicting, standards arise for the same information. This leads to costly and time-consuming harmonization efforts, which produce longer and more costly cycles.

A recent report from the Integrated Manufacturing Technology Roadmap[1] briefly describes a new approach in which software applications negotiate interfaces automatically. The authors called this approach self-integration. A recent report from the RAND Corporation on integration and interopoer-ability[2] contained a section titled "NIST's Evolving Role." The following excerpt is taken directly from that section.

"Are there ways of ensuring interoperability with lighter standards that do not have to specify as much, or, better yet, with translators and mediators that can dispense with many higher-level standards altogether? NIST itself can develop the parameters, corpora, tests, and testbeds that help measure the quality and fitness of ontologies and mediators."

In late 1999, several major manufacturing company members of the Open Applications Group (OAG)[3], a leading XML standards organization, issued a challenge to the organization's technology provider membership to 'show them XML-standards-based, real-time, B2B connectivity that can be used today to link their supply chains.' The "Vendor Challenge," a one-time event that occurred in late 2000 attracted more than 20 vendors and three major manufacturers — Boeing, Lucent, and Lockheed Martin. Each manufacturer provided a supply-chain integration scenario that the vendors used to demonstrate interoperability of their software tools based on the OAG interoperability specifications. Soon after that event a number of organizations, including OAG, RosettaNet, and the Automotive Industry Action Group (AIAG) approached NIST about developing a permanent place to test interoperability challenges – called the interoperability testbed. This testbed will have an on-going testing and experimenting capability and will be open for use to a large collection of potential stakeholders.

Technical Approach

Determining whether two software applications have the same semantic understanding of an information object is difficult. In a supply-chain environment, it is far more likely that semantically similar terms from two ontologies will agree on many, but not all, properties. Therefore, approximate or partial matching becomes a necessary part of the reasoning process. That process contains three major steps: measuring, negotiating, and mapping. In step one, measuring, we will develop a metric, a theory, and test methods, for comparing two information objects quantitatively. We will assess the applicability of the information uncertainty measures developed by Shannon, Stonier, and Zadeh. In addition, we will examine a number of quantitative and qualitative approaches to compute these measures. Step two, negotiating, will be done in conjunction with step one. We will use and expand the protocols being developed in ISO Technical Committee 184/Subcommittee 5/Working Group 1 (Industrial automation systems and integration/Architecture, communications and integration frameworks/Open systems application frameworks). In step three, mapping, we must develop syntactic and semantic translators between the two objects. We plan to continue the earlier work on mappings conducted as part of process specification language (PSL).

The research to achieve the ultimate goal of self-integration is necessarily multi-disciplinary. To be successful, that research must be grounded in the existing standards, technologies, and applications, yet build on evolving technologies such as the Semantic Web. Moreover, to be applicable, the research must be conducted jointly with all stakeholders including software vendors, manufacturers, standards organizations, and university researchers.

[1] Now maintained by the Integrated Manufacturing Technology Initiative [IMTI]. Roadmaps can be viewed at http://www.imti21.org/

[2] www.rand.org/publications/MR/MR1215/MR1215.chap6.pdf

[3] www.openapplications.org

With these complex research requirements in mind, we initiated development of a B2B Interoperability Testbed. This testbed will support four major activities:

- to help the Supply Chain Management (SCM) community better understand the capabilities of Semantic Web and other formal methods for self-integrating systems,
- to affect the development of Semantic Web technologies and standards while representing needs of the SCM community,
- to facilitate introduction and acceptance of those standards by the SCM community, and
- to demonstrate the potential of the new generation of self-integrating software applications.

The testbed will provide an infrastructure for interaction among manufacturing companies, software vendors, and standards organizations. The manufacturing companies will provide interaction scenarios (as a basis for supply chain integration testing) and requirements describing context for integration testing (e.g., messaging protocol specification). We will capture these scenarios and requirements to drive testbed development and make available a scenario repository. Both the manufacturing companies and software vendors will provide and operate nodes of the distributed testbed as no central authority will exist over the testbed operation. The customers and vendors will come together on an as-needed basis to assess, analyze, measure, and demonstrate on-demand integration of software applications that are used to operate supply chains. We will provide guidance for coordination of the interactions among the different nodes, develop conformance tests, provide test data, conduct integration tests, analyze these tests, and report results.

The context in which these projects get created depends on the expressed needs of the SCM community (i.e., technology pull) and/or on the perceived opportunity for a particular Semantic Web technology (i.e., technology push). Each project will have partners from the academic, business, and standards communities and will conclude with a demonstration. The testbed will provide a mechanism for the transfer of the results of research projects into commercial products that address real, supply-chain-integration problems using the Semantic Web.

Program Objectives and Technical Outputs

Objective 1:

By FY2003, develop scenarios, methods, and data sets for conformance testing. These will be necessary to conduct formal testing of commercial software applications for conformance to B2B specifications.

Technical Output

FY2003:
Papers describing the scenarios, methods, and data sets and successful demonstrations of their implementations.

Objective 2:

By FY2003, propose metrics and methods for comparing information objects. These are essential to determine whether two applications can share information — a requirement for self-integration.

Technical Outputs

FY2003:
Papers describing the metrics and methods.

FY2003:
Successful demonstrations of implementations.

Objective 3:

By FY2004, develop ontologies to support various B2B information exchanges. Ontologies, which will be used to define information objects formally, will provide the key underlying technology for self-integration.

Technical Outputs

FY2003:
The actual formal definitions of those objects in at least two different languages.

FY2003:
Papers that describe those definitions.

FY2003:
Demonstrations of automatic integration for at least one manufacturing scenario.

Objective 4:

By FY2005, propose negotiation protocols between software applications. These protocols will govern the conversations between software applications trying to achieve self-integration.

Technical Outputs

FY2003:
Candidate protocols defined.

FY2003:
Demonstrations that use the candidate protocols.

Objective 5:

By FY2005, complete agent-based demonstration. Distributed software agents will provide the implementation strategy for demonstrating self-integration using the outputs from previous objectives.

Technical Outputs

FY2003:
Papers that describe overall system architecture.

Anticipated Impacts

A successful program will have the following:

Industry impact

- Reduction in integration/product costs
- Faster time to market
- Broader access to customers/suppliers
- Increased focus on core business

NIST impact

- New class of standards and ways of testing conformance
- Fewer interface specifications means fewer standards committees
- Unified approach to measuring both physical and information objects

Accomplishments of the Past Year

- Completed roadmap for selected FY2003 projects.
- Completed draft report that describes a process for automating integration.
- Completed environment for testing syntax and choreography of pre-selected B2B applications and associated interface specifications.
- Completed several papers describing semantics-based integration based on simplified manufacturing scenarios and common ontologies built in DARPA agent markup language (DAML).
- Completed initial survey of quantitative and qualitative approaches to computing semantic equivalence metrics.
- Designed and implemented a server that uses DAML+OIL ontologies illustrating manufacturing web services.
- Developed and designed approach for semantic resolution in manufacturing e-commerce scenarios.
- Developed and implemented a coordination method in support of manufacturing B2B scenarios management.

- Learned and reported on the usage of nine inference engines and one modeling tool and reviewed numerous candidates for a basis ontology.
- Supported testing-related standards in OMG with technical contributions, statements to the Architecture Board, and procedural advice.
- Worked with the Manufacturing Domain Task Force of OMG to incorporate testability enhancements into manufacturing-related standards and validate their Interface Definition Language (IDL) on a regular basis.
- Chaired Test & Validation Special Interest Group (of OMG) and the Testability Work Group (of the Manufacturing Domain Task Force within OMG).
- Maintained IDL validation testbed and regularly validated the IDL for Product Data Management (PDM) Enablers, Computer Aided Design (CAD) Services, and the Distributed Simulation Systems Facility.
- Built and demonstrated a prototype tool (Similar Class Finder) for finding similar classes in different Universal Modeling Language (UML) class diagrams.
- Reviewed and reported on testing requirements for RosettaNet, Open Applications Group Integration Specification (OAGIS), and Organization for the Advancement of Structured Information Standards (OASIS) specifications.
- Delivered the Express-X Draft International Standard.
- Developed an implementation of the Express-X mapping engine in Express Engine (aka Expresso).
- Collaborating with National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL), provided guidance and developed models and software for two systems engineering standards development initiatives — The SC4 STEP (STandard for the Exchange of Product model data) model for systems engineering, and OMG's emerging specification of UML for Systems Engineering.
- Developed software for mapping of SPICE circuit simulations into ISO 10303-210 (Electro-Mechanical information model) for an upcoming demonstration with Boeing and Rockwell-Collins.
- Completed several demonstrations of successful specification testing based on customer-supplied manufacturing scenarios.

Workshops

25th Annual International Computer Software and Applications Conference – October 2001

David Flater presented a paper titled "Finding Similar Classes with a Simplified Metamodel"

35th Hawaii International Conference on System Sciences – January 2002

David Flater presented a paper titled "Impact of Model-Driven Standards,"

2002 International Conference on Information and Knowledge Engineering

David Flater and K.C. Morris presented a paper titled "Harmonized Conformance Testing for Product Data Managers"

PERMIS Conference – August 2002

Larry Reeker and Al Jones presented a paper titled "Measuring the Impact of Information Complex Systems"

Complexity Network Conference – April 2002

Al Jones, Larry Reeker, and Abhi Deshmukh presented a paper titled "On information, decisions and performance of complex manufacturing systems"

International Symposium on Manufacturing and Applications (ISOMA) Conference – June 2002

Al Jones, Larry Reeker, and Abhi Deshmukh presented a paper titled "Information: A Key to Supply Chain Performance"

Standards Participation

United Nations Centre for Trade Facilitation and Electronic Business (UN/CEFACT) E-Business Transition Working Group (eBTWG)

Editor of the Catalog of Common Business Processes documentation. The recently formed UN/CEFACT ebTWG initiated the Catalog of Common Business Processes project to define a useful taxonomy and methodology for mapping industry business processes onto the taxonomy.

OMG Manufacturing Domain Task Force

Participant in OMG's Manufacturing Domain Task Force (Mfg DTF), an organization responsible for setting the overarching strategy for the working groups that comprise the task force. Specific activities include:

- OMG Mfg DTF, PDM Working Group – participated in issuing Request for Information (RFIs), Request for Proposals (RFPs) and developing standards for PDM component interface definitions.
- OMG Web Ontology - Revived Ontology working group at OMG level. Developed mission, planned deliverables, and actors identified to produce those deliverables. Will participate in one or more mappings from OMG modelware — UML, MOF, and XMI — to DAML and Web Ontology Language (OWL).
- Testability Work Group - Incorporated testability enhancements into manufacturing-related standards and validate their IDL on a regular basis.

W3C Web Ontology Working Group

Provided an extensive review of the proposal document for a UML Presentation Syntax for OWL.

Open Applications Group

OAG is a consortium of enterprise applications software vendors (i.e., Enterprise Resource Planning (ERP) vendors) who have created common standards for the integration of enterprise business applications. This group produced the OAGIS, which is a requirements definition of information to be exchanged among ERP systems. The requirements specified in OAGIS are very relevant to the OMG ERP effort.

Program Manager:
Charles McLean

FTEs:	8.5
Program Funding:	$887 K

FY2003 Projects

- Distributed Manufacturing Simulation Architectures and Interfaces
- Distributed Manufacturing Simulation Prototypes
- Manufacturing Simulation Standards Support
- SEI TIDE Simulation Modeling Project
- Simulation of Manual Manufacturing Operations
- Modeling and Simulation for Emergency Response

MANUFACTURING SIMULATION & VISUALIZATION

Program Goal

By 2005, establish an initial set of standard interfaces and develop conformance tests for manufacturing simulation to support the rapid construction of

- distributed manufacturing simulation systems based upon a High Level Architecture (HLA) foundation; and
- manufacturing simulation models based upon a neutral data interface formats and a library of simulation components that are adopted by simulation software vendors in future product offerings.

Customer Need

Simulation is a powerful tool for letting designers imagine new systems and allowing them to both quantify and observe behavior. Whether the system is a production line, an operating room or a emergency-response system, simulation can be used to study and compare alternative designs or to troubleshoot existing systems. With simulation models, we are free to imagine how an existing system might perform if altered or imagine, and explicitly visualize, how a new system might behave before the prototype is even completed.

Industry experts on manufacturing technology recognize the importance of simulation and visualization. Various industry roadmap efforts, such as the Integrated Manufacturing Technology Roadmapping1 (IMTR), National Research Council (NRC) Visionary Manufacturing Challenges, and National Electronics Manufacturing Initiative (NEMI) made strong recommendations for research in modeling and simulation technology. For example, the IMTR Study stated:

> "Modeling and simulation (M&S) are emerging as key technologies to support manufacturing in the 21st century, and no other technology offers more than a fraction of the potential that M&S does for improving products, perfecting processes, reducing design-to-manufacturing cycle time, and reducing product realization costs."[2]

[1] Now maintained by the Integrated Manufacturing Technology Initiative [IMTI].
2 "IMTR Roadmap for Modeling and Simulation," November 1998, http://imti21.org/Documents/Roadmaps/MS.pdf, page 8.

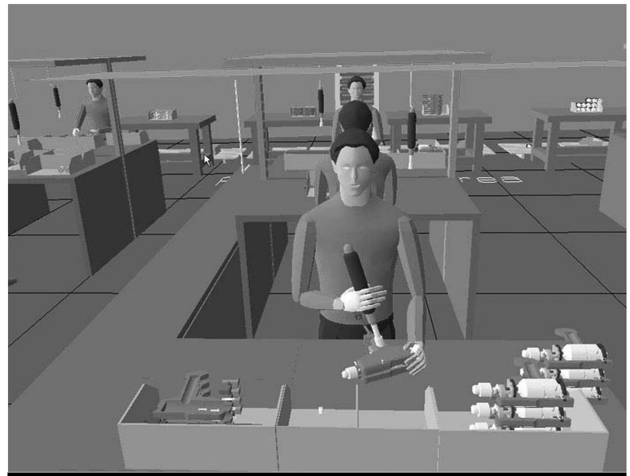
Simulation and modeling were also identified recently by the NRC, as one of two breakthrough technologies that will accelerate progress in addressing the grand challenges facing manufacturing in 2020. The study recommends that standards be established for the verification, validation, and accreditation of modeling tools and models (including geometric models, behavioral models, process models, and cost and performance models).

It also recommends research and development (R&D) of

> ‘standards for software compatibility, including methods to make data accessible (protocols, security, format, interoperability), interactive 3-D simulation-based visualizations of complex structures integrating behavioral, organizational, and people issues, methods to merge historical data with simulation systems, and simulation of alternative business processes.”[3]

The NRC report, titled “Defense Manufacturing in 2010 and Beyond: Meeting the Changing Needs of National Defense” recommended that R&D be augmented in four priority areas, one of which is “modeling and simulation-based design tools.” In a discussion on simulation and modeling, the report goes on to state that:

> “Techniques such as variation simulation analysis (VSA) and factory floor layout simulation can improve product performance. Assembly modeling can be used to complement simulations to determine if changing the order of steps in the assembly of a complex product can lead to labor savings and reduce variation. Combining three-dimensional product modeling with simulation techniques can help determine the cost of alternative manufacturing processes.”



Simulation of a Power Tool Assembly Line

The Semiconductor Research Corporation (SRC) Factory Sciences Board identified manufacturing simulation as a high payback area. It recommends research on distributed simulation. It suggests that research should focus on

> “Mechanisms to support the creation of collections of simulations that are linked through open standards. These simulations might be as differing levels of fidelity and abstraction, and may model different commercial partners’ operations, such as the supplier and the customer. The mechanisms must address the need for partners to expose only part of their simulation models and data, while shielding proprietary information.”

Although these studies recognize the potential of manufacturing simulation and visualization, there are a number of technical and economic barriers that hinder the use of this technology. In particular, industry expenses for implementing simulation technology are much greater than the cost of computing hardware, peripheral devices, software licenses, and maintenance. Typically companies must factor in the cost of salaries and training for simulation and support staff, translation of existing company data into the new system, integration of applications, and development and maintenance of models.Vendors and industrial users alike recognize that the development and maintenance of models of their production systems and resources is very costly.

3 “Visionary Manufacturing Challenges for 2020”, National Research Council, Washington, DC 1998, pages 5, 63, and 114.

For example, a single engineer may need four to six weeks to develop a detailed simulation model of a single machine tool. Models must now be custom-developed for each simulation software package.

How can the cost of the lengthy simulation development process be reduced? The solution would appear to be to simplify the problem by making models modular and creating reusable simulation-model code and data. The development of neutral, vendor-independent data formats for storing simulation models could greatly improve industry's access to simulation technology by enabling the sharing and re-use of models. Individual companies, simulation vendors, equipment and resource manufacturers, consultants, and service providers could use such neutral simulation model formats to develop sharable models. Neutral formats would help enlarge the market for simulation models and make their development a viable business enterprise.

Technical Approach

NIST will develop standardized interfaces, component model libraries, and modeling techniques to help reduce the cost and increase the accessibility of manufacturing simulation technology. A major focus will be the identification and specification of data interfaces for various manufacturing simulation applications. This program grew out of projects in engineering tool integration and scheduling system integration funded by the Systems Integration for Manufacturing Applications (SIMA) program and the Navy Manufacturing Technology Program.

The program will: 1) identify critical manufacturing process and system simulation domains and associated types of simulation software applications; 2) analyze current and future trends for simulation and testing technology; 3) establish specification and testing methods, models, and metrics for validating simulation systems interfaces; 4) identify tools and models to be used in the specification development, prototyping, and testing processes; 5) construct a test bed containing simulation applications, prototype integration, testing tools, and test cases; 6) specify and develop architectures, data models, and interface specifications for integrating simulation applications, component modules, and reference libraries; 7) conduct experimental tests, industry demonstrations, and reviews to substantiate the validation and testing process itself; and 8) promote specifications as candidate standards within the national and international standards community.

In the end, our program will result in the specification of:

- simulation study templates for addressing classes of simulation problems,
- building block modules of manufacturing system components to be used in the templates,
- interfaces for interconnecting simulation component modules together,
- libraries of simulation reference data sets, and
- standards for each of these elements would reduce costs by allowing solutions to be shared by all software vendors and industrial users.

Program Objectives and Technical Outputs

Objective 1:

By FY2003, establish a new consortium of simulation software vendors to continue the coordination and simulation standards development activities initiated by NIST with those vendors under the global Intelligent Manufacturing Systems (IMS) Modeling and Simulation Environments for Design, Planning and Operation of Globally Distributed Enterprises (MISSION) Project.

Technical Output

FY2003:
Consortium of simulation software vendors established that will serve to focus standards activities, provide feedback, technical support, and promote standards within industry.

Objective 2:

By FY2004, establish standards status for an architecture and integration interfaces for interconnecting discrete event simulation systems using extensions to the HLA.

Technical Outputs

FY2003:
Integration of Distributed Manufacturing Simulation (DMS) Adapter software with selected commercial simulation systems from our vendor partners to provide an initial commercial capability that will enable the implementation of distributed manufacturing simulations based on the HLA Run-Time Infrastructure.

FY2003:
Distributed supply chain simulation using various commercial simulators and adapter demonstrated thus illustrating the viability and practical use of the DMS adapter to solve real-world simulation problems.

FY2004:
Consensus standard for DMS Adapter interface service calls established that will allow vendors to implement their own HLA adapter interfaces.

FY2005:
Conformance test for DMS Adapter service calls established that will ensure that vendor implementations comply with the adapter specification, thus providing interoperability between different commercial products.

Objective 3:

By FY2004, develop and publish an initial set of data models and exchange format specifications for simulation transactions for mechanical product manufacturing supply chains.

Technical Outputs

FY2003:
A report identifying existing or evolving standards that may be used to develop simulation transaction standards to ensure that any new proposed simulation standards take into account appropriate existing standards.

FY2003:
A specification document that defines simulation interfaces for machine shop data.

FY2004:
A specification document that prescribes a transaction-based interface that can be used as the basis for an industry standard to implement distributed supply chain simulations.

Objective 4:

By FY2005, create a mechanism and structure for encoding simulation models in a neutral format that can be used to import and export models of manufacturing production and support systems among multiple discrete event simulation software systems.

Technical Outputs

FY2003:
A document that identifies requirements and solutions for the implementation of a neutral model format for simulation components.

FY2004:
An initial format for neutral models and test software to import and export the model from a test set of commercial manufacturing simulators.

FY2005:
An initial consensus standard established for the neutral simulation model format that can be used by industry in commercial simulation products and reference libraries.

Anticipated Impacts

This program is the only national or international effort specifically directed at developing candidate standards for the manufacturing simulation software market. Economic analysts estimate that the current size of the manufacturing simulation and visualization software market is approximately $650 M. The development of new simulation interface standards will help increase the deployment of simulation technology. Interface standards will improve the accessibility of this technology by helping to reduce the expenses associated with acquisition and deployment, minimize model development time and costs, and provide new types of simulation functionality that are not available today. The manufacturing industry will see tangible benefits in the advancement of the simulation and visualization software applications through increased speed to market, reduced costs, and increased efficiency.

Accomplishments of the Past Year

- Simulation Study Taxonomy report published as a paper for the Winter Simulation Conference titled "Framework for Standard Modular Simulation."
- A initial set of Universal Modeling Language (UML) and Extensible Markup Language (XML) data models for machine shop simulation defined with partners at Software Engineering Institute, Carnegie-Mellon University, and the Kurt J. Lesker Company.
- Obtained initial agreement with software vendors on the formation of a simulation standards consortium.
- Completed public demonstration of NIST Distributed Manufacturing Simulation Adapter and the IMS MISSION Consortium Open Day Meeting in Tokyo, Japan.
- Completed initial distributed supply chain simulation demonstration with partners from University of Arizona and Florida International University.
- Developed a virtual reality simulation model of a mechanical products production line that demonstrates data requirements for that type of simulation.
- Papers describing an architecture for a generic machine shop simulator and the process and data requirements for virtual reality simulation models of mechanical parts production lines were completed for the Winter Simulation Conference.
- Organized an invited session on "Simulation Standards: Integration Interfaces, Model Accreditation, and Analyst Certification" at the Winter Simulation Conference.

Workshops

A workshop entitled "Simulation and Modeling for Emergency Response" is planned for March 4-6, 2003. The workshop will investigate issues in integrating simulation systems in support of homeland defense and emergency response.

Other Information

The program establishes collaborations with industry, software vendors, universities, and guest researchers to leverage resources and bring diverse technical expertise and backgrounds to the program. External collaborators include the international IMS Program, the Navy National Shipbuilding Research Program (NSRP), Software Engineering Institute (SEI) TIDE Program, Institute of Electrical and Electronic Engineers (IEEE) Learning Technology Standards Committee, and the Object Management Group (OMG) Special Interest Group in Distributed Simulation (SIMSIG). A number of major U.S. simulation companies participate in and support the projects, including: Autosimulations, Delmia, Rockwell Automation - Systems Modeling Corporation, Promodel, KBSI, EDS (parent of Engineering Animation Inc.-EAI). Vendors participated in program review activities, provided software and technical support resources. Program staff established dialogs and obtained support from the top management in many of these companies who will help ensure the implementation and impact of project results. A number of universities and other research organizations are also participating in the program. The program staff also collaborates with NIST personnel within the Information Technology Laboratory and Building and Fire Research Laboratory.

Standards Participation

OMG SIMSIG

Program staff members supported the standardization activities within the OMG SIMSIG that is part of its Manufacturing Domain Task Force. SIMSIG is developing of Common Object Request Broker Architecture (CORBA)-based interfaces for the implementation of distributed simulations. During this period, SIMSIG established the High Level Architecture (HLA) as a standard. In FY2003, a member of the program staff, Frank Riddick, will assume leadership of the OMG SIMSIG organization. This program is working with Defense Modeling and Simulation Office (DMSO) to evaluate the suitability of HLA standard to manufacturing simulation.

IEEE Learning Technology Standards Committee

As a result of previous work funded by NIST's Advanced Technology Program (ATP), this group has become involved in not only simulation standards development but also in those standards in the learning technology area. Swee Leong participates in and collaborates with the IEEE Learning Technology Standards Committee. There is considerable interest by the committee in our work and they requested and received copies of our experimental prototype software that can be used to integrate simulation with other applications.

Program Manager:
David J. Evans

FTEs:	10
Program Funding:	$2,415 K

FY2003 Projects

- Acoustical Intercomparisons, Standardization and Legal Metrology
- Acoustical Metrology
- Automation of 27 kN (6 klbf) Dead Weight Machine
- Customer Feedback Survey
- Emergency Vehicle Sirens
- Force Intercomparisons, Standardization and Legal Metrology
- Force Metrology
- Hearing Aid Metrology
- Mass Intercomparisons, Standardization and Legal Metrology
- Mass Metrology
- Mechanical Vibration and Shock (V&S) Metrology
- Mechanical V&S Intercomparisons and Standardization

MECHANICAL METROLOGY

Program Goal

Provide support for the most critical of measurement services in acoustics, force, mass, and vibration through the provision of calibration services, traceability, and physical standards; improvement in the realization of existing quantities; participation in relevant activities of the International Committee of Weights and Measures (CIPM); and the harmonization of international and national standards.

- In acoustics, the objectives are to realize and disseminate the unit of sound pressure; develop and implement apparatus for reducing the uncertainty in pressure-response calibration of microphones; participate in various national and internation standards activities; and continue to develop and implement methodologies and systems for testing and evaluating the electroacoustic performance of hearing aids.
- In the area of force, the objectives are to realize and disseminate the unit of force; provide National Type Evaluation services; develop and implement systems to improve the operational efficiency of the dead weight machines; and participate in national and international standards activities.
- With respect to mass, the objectives are to disseminate the unit of mass; maintain the U.S. International Prototype Kilogram; develop and implement systems for participation in 50 kg and density comparisons; participate in national and international standards activities; and calibrate the large weights.
- In vibration, the objectives are to realize and disseminate the unit of acceleration; develop and implement an apparatus for reducing the uncertainty in the calibration of accelerometers; and participate in national and international standards activities.
- Ultrasonic measurement services are being phased out.

Customer Needs

This program directly supports the needs and demands of U.S. customers for traceability directly to the top of the U.S. measurement hierarchy, including requirements in U.S. law or regulation; maintenance of NIST's position as a global leader in measurement in CIPM, the CIPM Mutual Recognition Arrangement (MRA), International Organization of Legal Metrology (OIML), International Organization for Standardization (ISO), and International Electrotechnical Commission (IEC); and the requisite recognition of U.S. metrology by the international community.

Calibrations and tests are performed for customers in the industrial, governmental, and educational sectors including the aerospace industry, automotive industry, construction industry, nuclear power industry, pharmaceutical industry, instrument manufacturers, the state weights and measures labs, the U.S. Department of Commerce, Department of Defense, Department of Energy (DOE), Department of Labor, and university research laboratories. The U.S. Dept. of Veterans Affairs (VA) has sponsored work in the development, characterization, and documentation of methodologies for testing and evaluating the electroacoustic performance of hearing aids for an extended period of time as ever-more sophisticated hearing aids and arrays demand the development of more complex testing methods.

Technical Approach

To achieve its objectives, the program will continue to realize and/or maintain the national standards for mechanical quantities and improve its facilities, which include a 450 m^3 acoustic anechoic chamber, a world-class force laboratory with six deadweight machines that generate discrete forces over a range of 44 N to 4.448 MN, a world-class clean room mass laboratory with tight environmental controls, and other specialized laboratories and equipment. The program will strive to provide timely and accurate physical measurement services and perform short-term development to meet customer and standards needs.

These efforts will be complemented by the development of quality control tools that will be incorporated into quality manuals and/or publications throughout all of the services in accordance with NIST policy. Also, services will conduct workshops, customer surveys, or both to assess customer needs and satisfaction, and to explore mechanisms for improving the delivery of measurement services. The adequacy of current facilities and equipment will periodically be reviewed, priorities established, and improvements undertaken as resources allow.

FY2003 Projects Continued

- Primary Accelerometer Calibration System
- Quality Assurance and Maintenance of the Mass Unit
- Quality Assurance in Acoustical Metrology
- Quality Assurance in Force Metrology
- Quality Assurance in Mechanical V&S Metrology
- Termination of Ultrasonics Measurement Services
- Ultrasonics Intercomparisons and Standardization
- Ultrasonics Metrology
- Upgrade Microphone Pressure Calibration System

Additionally, the program will continue to perform research and development (R&D) that leads to new methodologies for improved measurement services, methods for new quantities or expanded ranges, more fundamental realizations of units, and new measurement methods and data in support of industrial product development. Furthermore, as new measurement techniques or unit realizations are developed and documented, measurement services will work to incorporate these improvements or new techniques into new and/or existing services. This effort is largely measurement-based, but includes important theoretical, analytical, and computational aspects.

Program Objectives and Technical Outputs

Objective 1:

By FY2003, in accordance with the VA, develop, characterize, and document methodologies for testing and evaluating the electroacoustic performance of hearing aids.

Technical Output

FY2003:
Hearing Aid Metrology - Documented procedures for initial tests of digital hearing aids and measurement results of VA-supplied digital and analog hearing aids.

Objective 2:

By FY2003, provide special measurements, evaluations, and standards development for sponsors of work funded outside of the NIST Calibration Services.

Technical Output

FY2003:
Emergency Vehicle Sirens – "Phase Two" revision of Society of Automotive Engineers (SAE) J1849 Recommended Practice; measurements supporting further development of this recommended practice as needed; and project status and trip reports for the NIST Office of Law Enforcement Standards (OLES).

Objective 3:

By FY2004, develop user-friendly, interactive software for the analysis and reporting of mass calibration data based on demands of customers including the US Army, Air Force, Navy, National Aeronautics and Space Administration (NASA), DOE labs, States Weights and Measures labs, and aerospace metrology labs.

Technical Output

FY2004:
Mass Software – software package released with provision of training on its use.

Objective 4:

By FY2004, terminate all ultrasonics measurement services contained in NIST SP 250 Chapter 5 sections H, I, and J in an orderly, timely, and informed manner.

Technical Output

FY2004:
Termination of Ultrasonics Measurement Services - Requisite information and documentation needed that is in compliance with NIST procedures for the Termination of NIST Measurement Services.

Objective 5:

By FY2004, reduce by up to one-half the FY2001 estimated uncertainty of NIST SP 250 sinusoidal accelerometer calibrations in the frequency range of 10 Hz to 10 kHz.

Technical Output

FY2004:
Primary Accelerometer Calibration System - a new primary accelerometer calibration system developed with uncertainty estimate(s).

Objective 6:

By FY2005, assess customer needs and satisfaction relative to each of the measurement services through agency-approved customer feedback forms and/or studies.

Technical Output

FY2005:
Customer Feedback Survey - A report summarizing findings of customer feedback forms.

Objective 7:

By FY2005, perform calibrations and special tests with uncertainties equal to or better than those specified in publication NIST SP 250; provide 90% or better on-time delivery of reports of calibrations and special tests to all customers.

Technical Outputs

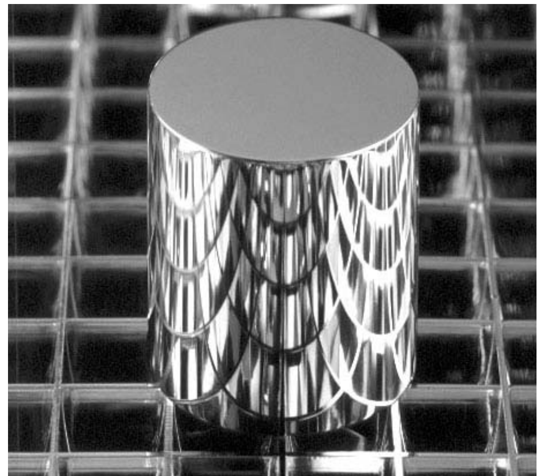
Provision of services, calibrations and special tests for:

FY2003 - FY2005:
Acoustical Metrology in the pressure field over the frequency range of 50 Hz to 20 kHz, and in the free field over the frequency range of 2.5 kHz to 20 kHz.

FY2003 - FY2005:
Force Metrology in the range of 44 N to 53 MN.

FY2003 - FY2005:
Mass Metrology in the range of 1 mg to 27,000 kg and for the measurement of the density of solids.

FY2003 - FY2005:
Mechanical Vibration and Shock Metrology in the frequency range of 1 Hz to 20 kHz.



The U.S. International Prototype Kilogram maintained by the Mechanical Metrology Program

Objective 8:

By FY2005, ensure traceability and comparability of U.S. physical and documentary standards in mechanical metrology to those of other nations.

Technical Outputs

FY2003 - FY2005:
Acoustical Intercomparisons, Standardization and Legal Metrology - Report on key comparison in acoustics (CCAUV.A-K1); participation in the CCAUV key comparisons in acoustics; participation in the Interamerican System of Metrology (SIM) pistonphone regional comparison in acoustics; U.S., NIST, U.S. Expert, or Technical Advisory positions, votes and comments delivered in the area of acoustics to the CCAUV, SIM Metrology Working Group (WG) 9, IEC TC29 on Electroacoustics and its working groups on Calibration of Microphones and Hearing Aids, U.S. National Committee (USNC)/IEC for TC29, Secretariat of the U.S. Technical Advisory Groups (TAG) for IEC TC29, ANSI Committees on Acoustics, S1, and Bioacoustics, S3, Acoustical Society of America Committee on Standards (ASACOS), and Standards Committee Plenary Group.

FY2003 - FY2005:
Force Intercomparisons and Standardization - Participation in the 100 kN and 1 MN key comparisons; pilot the 2 MN and 4 MN key comparisons; U.S., NIST, or U.S. Expert positions, votes, and comments delivered in the area of force to the Consultative Committee on Mass and Related Quantities (CCM), CCM WG on Force, SIM MWG 7, U.S. National WG (USNWG)/OIML TC9/WG1, and ASTM E28.01.

FY2003 - FY2005:
Mass Intercomparisons, Standardization and Legal Metrology - Documentation on the national and SIM comparison for mass delivered; uncertainty budgets for a new 50 kg mass comparator and a new density system for the 50 kg key comparison and density bilateral comparison; participation in the 1 kg plus multiples and sub-multiples key comparison; pilot the SIM 1 kg regional comparison; U.S., NIST, U.S. Expert, or Technical Advisory positions, votes, and comments delivered in the area of mass and solid density to the CCM, CCM WG on Mass, CCM WG on Density, SIM MWG 7, and ASTM E41.06.

FY2003 - FY2005:
Ultrasonics Intercomparisons and Standardization - Chairperson, Liaison, U.S., NIST, or U.S. Expert positions, votes, and comments delivered in the area of ultrasound and Non-destructive Testing (NDT) to the CCAUV, Secretariat of the U.S. TAG for ISO TC135 NDT, ISO TC135/SC3 (Acoustical methods), IEC TC87 (Ultrasonics), ASTM E7 NDT, E7.04 (Acoustic Emission Method), and E7.06 (Ultrasonic Method), and ASTM E28 (Mechanical Testing), E28.05 (Residual Stress), and E28.13 (Dynamic Modulus Measurements).

FY2003 - FY2005:
Mechanical Vibration and Shock (V&S) Intercomparisons and Standardization - Report for key comparison in vibration (CCAUV.V-K1); report for the regional comparison in vibration (SIM.AUV.V-K1); participation in the SIM low-frequency regional comparison in vibration; U.S., NIST, or U.S. Expert positions, votes, and comments delivered to the CCAUV, SIM Metrology WG 9, ISO TC108 on Mechanical V&S and its working groups on Terminology and Stationary and Non Stationary Signal Processing, TC108/SC3 on Use and Calibration of Vibration and Shock Measuring Instruments and its working groups on Calibration of V&S Transducers and Vibration Condition Monitoring Transducers and Instrumentation, the Secretariat of the U.S. TAGs for ISO TC108 and TC108/SC3, the ANSI Committee on Mechanical Vibration and Shock, S2, the ASACOS Steering Committee, ASACOS, and the Standards Committee Plenary Group.

Objective 9:

By FY2005, maintain NIST Guidelines on Quality Assurance.

Technical Outputs

FY2003 - FY2005:
Quality Assurance in Acoustical Metrology - Primary calibrations of NIST reference standard microphones used in support of NIST SP 250 acoustical calibrations.

FY2003 - FY2005:
Quality Assurance in Force Metrology - Intercomparisons of the six deadweight machines with quality assurance charts; secondary calibrations of the eight Solartron digital multimeters (DMMs) with quality assurance charts for each; primary calibration of the Solartron DMM provided by the NIST Electricity Division.

FY2003 - FY2005:
Quality Assurance in Mass Metrology and Maintenance of the Mass Unit - NIST standards calibrated to maintain traceability to the International Prototype Kilogram; the large weights calibrated in pounds.

FY2003 - FY2005:
Quality Assurance in Mechanical Vibration and Shock Metrology - Periodic calibrations of NIST reference standard accelerometers on all calibration systems used in support of SP 250 sinusoidal vibration measurement services.

Objective 10:

By FY2005, research and develop the methodology and apparatus for reducing by one-third the FY2001 estimated microphone calibration uncertainty at critical midband frequencies (250 Hz to 1 kHz).

Technical Output

FY2005:
Upgrade Microphone Pressure Calibration System - an upgraded microphone pressure calibration system developed with uncertainty estimate(s).

Objective 11:

By FY2005, complete implementation necessary to improve the operational efficiency of the 27 kN deadweight machine.

Technical Output

FY2005:
Automated Dead Weight Machine - The 27 kN (6 klbf) Dead Weight Machine automated.

Anticipated Impacts

The international equivalence of measurement services, recognition of calibration certificates and measurement capabilities, and acceptance of test and calibration methodologies will be maintained through participation in international and regional intercomparisons, international and regional consultative committees and their working groups, the MRA, and national and international work in documentary standards development organizations.

Accomplishments of the Past Year

NIST SP 250 Measurement Services

A total of 659 calibrations and special tests were performed for 141 distinct entities in the industrial, governmental, and educational sectors.

Customer Feedback Survey

Since approximately January 2000, a customer feedback form has been distributed with each report of calibration or special test provided by the program. An internal report summarizing and documenting the results received from the distribution of these forms was completed. The report concluded that 83 percent of the feedback ranged from very good to A+. Other responses included good to informative/helpful. No negative responses were received.

Hearing Aid Metrology

The measurement protocol and data reduction and analysis software was validated for digital hearing aids with noise suppression features including the development of software to compute a tally for procurement purposes from the measurement results of such hearing aids.

Emergency Vehicle Sirens

The final "phase one" revision covering the parts of the Society of Automotive Engineers (SAE) Recommended Practice SAE J1849 - Emergency Vehicle Sirens involving electronic siren systems with a single loudspeaker and electromechanical sirens was balloted, approved, and published.

International Meetings of the CIPM CCM and the CCM Working Group on Force Held at NIST

Representatives from the National Metrology Institutes of Germany, France, England, Belgium, Finland, Mexico, Turkey, China, Japan, Korea, and Kenya participated in a meeting focusing on the results of a recently completed key comparison, planning for future key comparisons, and the status and review of the Calibration and Measurement Capabilities (CMC) tables for force measurements.

International Meeting of SIM Working Group on Mass and Related Quantities Held at NIST

Representatives from Mexico, Jamaica, Chile, Brazil, Nicaragua, and Ecuador, and the United States participated in the working group meeting at which the subgroup on Force, Torque, and Hardness was restructured, and a plan to link SIM key comparisons to the CIPM key comparisons was developed.

International and Regional Intercomparisons

The second drafts of the reports on the first key intercomparisons in acoustics, ultrasound, and vibration were tentatively approved subject to minor revisions. An extensive statistical analysis involving the pilot lab and NIST was performed to properly assess the reference values and their relative uncertainties for the vibration key comparison. The transducers to be used in the key comparison in force from 2 MN to 4 MN were obtained, characterized, and put into circulation.

MRA Calibration and Measurement Capability and the SIM

The CMCs for acoustics, force, mass, solid density, ultrasound, and vibration were published in Appendix C of the MRA.

Documentary Standards

Two international standards on primary calibration of vibration and shock transducers by reciprocity and interferometry were published. Four international standards on pressure calibration of working standard microphones, specifications for sound level meters, specifications for personal sound exposure meters, and acoustic emision vocabulary were published. A national standard and a technical report on weighting networks for acoustical measurements, and bubble detection and cavitation monitoring were published.

Expanded and Improved Mass Measurement Capabilities

The installation and initial testing of a new 64 kg mass comparator that will be used to expand and improve metric measurement capabilities between 10 kg and 64 kg was completed. The uncertainty in mass measurements between 10 kg and 64 kg is expected to be reduced by an order of magnitude.

Primary Accelerometer Calibration System

A new primary calibration system enabling the absolute determination of the complex sensitivity of accelerometers was received, and an initial performance evaluation of the system and some of its components were completed. The results of the initial tests indicate that changes to the system software, signal processing, electronic components, and mechanical structure(s) will be required for the system to meet NIST requirements.

NIST Contributions Recognized in R&D 100 Award

An R&D 100 Award was awarded to Simpex Technologies, Inc., NIST, the Johns Hopkins Applied Physics Laboratory, and the DOE Idaho National Engineering Laboratory for the Micro Laser Ultrasonic Bond Detection System. NIST has maintained a CRADA with Simpex Technologies since 1997 to provide advice regarding ultrasonic excitation and detection schemes, and signature analysis for the bond detection system .

Standards Participation

ANSI S1 Acoustics

Organizational Member; S1/WG1 Standard Microphones and their Calibration: Chair; S1/WG21 Electromagnetic Susceptibility of Acoustical Instruments: Member

ANSI S2 Mechanical Vibration and Shock:

Vice Chair and Organizational Member; S2/WG2 Terminology: Chair; S2/WG3 Signal Processing Methods: Member; S2/WG5 Use and Calibration of Vibration and Shock Measuring Instruments: Chair

ANSI S3 Bioacoustics

Organizational Member; S3/WG48 Hearing Aids: Member

ASACOS

Member

ASTM E7 Nondestructive Testing

Member; E7.04 Acoustic Emission: Member; E7.06 Ultrasonics: Member.

ASTM E28 Mechanical Testing

Member; E28.01 Calibration of Mechanical Testing Machines and Apparatus: Member; E28.05 Residual Stress: Member; E28.13 Dynamic Modulus Measurements: Member.

ASTM E41.06 Weighing Devices

Member

CIPM

Consultative Committee on Acoustics, Ultrasound and Vibration (CCAUV): Delegate; Consultative Committee on Mass and Related Quantities (including force) (CCM): Delegate; CCM WG on Mass: Member; CCM WG on Density: Member; CCM WG on Force: Member.

SIM

MWG7 Mass & Related Quantities: Chair; MWG9 Acoustics and Vibration: Member.

IEC TC29 Electroacoustics

Chair U.S. Delegation; USNC/IEC for TC29: Technical Advisor; TC29/WG5 Measurement Microphones: Member.

ISO TC108 Mechanical Vibration and Shock

Chair U.S. Delegation; TC108 U.S. TAG: Chair; TC108/WG1 Terminology: Member; TC108/WG26 Signal Processing Methods for the Analysis of Stationary Mechanical Vibration: Convener; TC108/WG27 Signal Processing Methods for the Analysis of Non-Stationary Mechanical Vibration and Shock: Member; TC108/SC3 Use and Calibration of Vibration and Shock Instrumentation: Chair U.S. Delegation; TC108/SC 3 U.S. TAG: Chair; TC108/SC3/WG6 Calibration of Vibration and Shock Transducers: Member; TC108/SC3/WG10 Vibration Condition Monitoring Transducers and Instrumentation: Member.

ISO TC135 Nondestructive Testing

Alternate Chair U.S. Delegation; ISO TC135/SC3 Acoustic Methods: Chair; ISO TC135/SC3: liaison to IEC TC87 Ultrasonics.

OIML TC9 Instruments for Measuring Mass and Density

Technical Advisor to U.S. Voting Member; OIML TC9/SC3 Weights: Technical Advisor to U.S. Voting Member; OIML TC13 Measuring Instruments for Acoustics and Vibration: Technical Advisor to U.S. Voting Member; USNWG/OIML TC9/WG1 Load Cells: Member.

SAE Emergency Vehicle Siren (J1849) Task Force

Vice Chair.

FY2003 Measurement Services

Calibrations and Special Tests

Provide calibrations and special tests as described under Mass Standards, Force Measurements, Vibration Measurements, Acoustic Measurements, and Ultrasonic Measurements in the NIST Calibration Services Users Guide, SP 250.

Research Facilities

Provide tests and measurements on an as-needed basis in special NIST Research Facilities such as the NIST Acoustic Anechoic Chamber.

Testing

Load Cell Evaluation - Provide evaluations of prototype load cells in accordance with both national (NTEP) and international (OIML R60) standards.

Hearing Aid Testing - Provide testing of hearing aids for the VA.

Nanometer-Scale Metrology

Program Manager:
Michael T. Postek

FTEs:	11.9
Program Funding:	$1,866 K

2002 Projects

- Atom-based Dimensional Artifacts
- Integrated Dimensional and Electrical Metrology of Nanostructures
- Model-based Linewidth Metrology
- Optical Overlay Metrology Research and Standards
- Optical Linewidth Standards for Integrated Circuit (IC) Dimensional Metrology
- Scanning Electron Microscope (SEM) Dimensional Metrology

Program Goal

Provide to the U. S. microelectronics industry, directly or indirectly, reference measurements, reference standards, and infrastructural metrology identified as necessary to help the industry to continue the historical rate of dimensional reduction and to subsequently realize its production goal of sub-100 nm devices by 2005 and beyond, including:

- providing Standard Reference Materials (SRMs) and metrology methodology for photomask critical dimension, wafer critical dimension and overlay metrology;
- developing three-dimensional (3D) structures of controlled geometry whose dimensions can be measured and traced directly to the intrinsic crystal lattice; and
- improving the accuracy of critical dimension and overlay measurements in semiconductor manufacturing.

Customer Needs

NIST is responsible to U.S. industry for developing length-intensive measurement capabilities and calibration standards in the nanometer-scale regime. The Nanometer-Scale Metrology program carries out projects ranging from scanning probe microscopy (SPM), optical microscopy, interferometry, and scanning electron microscopy (SEM) to traditional linescale interferometry that maintains the NIST capability for length-scale measurements at a world-class level. The industrial relevancy of the research and standards provided by this program has resulted in a large number of industrial interactions, especially within the semiconductor industry, notably through work funded by International SEMATECH (ISMT).

There is a demonstrated need voiced by the semiconductor, flat panel display, and high-density memory manufacturing industries for measurement methods and artifacts whose dimensions are known with nanometer-scale accuracy. The NSM program strives to meet this need and support the infrastructure of industrial metrology through the application of the NIST expertise to nanometrology. Of the industries served, the strongest push and clearest direction is provided by the ever-demanding needs of the semiconductor industry. Solutions that meet the advanced needs of the semiconductor industry can be rapidly applied to other industrial sectors. The International Technology Roadmap for Semiconductors (ITRS) currently directs the semiconductor industry and, by extension, strongly influences this program. The semiconductor industry and especially the instrument-manufacturing base are both driven by the ITRS roadmap.

The needs outlined within the ITRS roadmap are broad, but several are being addressed within this program. Critical dimension (CD) and overlay metrology are high priorities in the ITRS and historically have been among the strengths of this program. Considering that the semiconductor industry is a $200 billion dollar industry that was expected to grow to $312 billion in 2003 and is supported by a huge manufacturer base, even small improvements in metrology can yield large savings and increased profits to the industry.

Technical Approach

Length measurements in the nanometer-scale regime are accomplished by a number of methodologies, including tunneling, atomic-force, electron, and visible and ultraviolet light microscopes. Computer modeling and standards development are also integral parts of the measurement process. The program also carries out research and development in potentially "disruptive technologies," such as high-pressure/environmental microscopy and nanotip emitters for scanning electron microscopy, and work on the potential of developing and incorporating intrinsic standards using the atomic lattice, fabrication of sub-50 nm calibration structures using unique lithographic techniques, and instrument performance characterization.

Program Objectives and Technical Outputs

Objective 1:

By FY2007, develop and implement in collaboration with industry a first-ever accurate shape sensitive linewidth computer model for improving the accuracy of linewidth measurements in semiconductor manufacturing.

Technical Outputs

FY2003:
A prototype shape-sensitive measurement system for industry CD-SEM delivered to ISMT.

FY2004:
Report of the test of the shape sensitive linewidth measurement system for polysilicon samples measured by industrial CD-SEMs.

FY2005:
Prototype method delivered to SEM instrument manufacturers.

FY2006:
Publication evaluating the performance of shape-sensitive linewidth metrology for resist structures on CD-SEMs.

FY2007:
Availability of the code on a NIST website and publication of the results of the commercial implementation demonstrating improved CD measurement accuracy through use of the NIST system.

Objective 2:

By FY2007, implement a mask-less lithography system capable of fabricating sub-100 nm test calibration structures and having the capabilities to perform simultaneous dimensional and electrical measurements using SPM techniques relevant to nanotechnology, microfluidics and for semiconductor industry applications.

Technical Outputs

FY2003:
A functional maskless, benchtop optical lithography system based on a Texas Instruments digital micromirror device overhead projector.

FY2004:
Functional microfluidic arrays with nanoscale features using combined maskless optical, SPM, and nano-imprint lithographies.

FY2005:
Prototype sub-100-nm pitch calibration scales; Large-scale replication of sub-100-nm pitch 1- and 2-D features demonstrated.

FY2006:
A publication on the results of the fabrication of nanostructures for supra-molecular chemical templates for the microfluidic systems.

FY2007:
Functional optical and electrical nanostructures integrated into microfluidic systems; simultaneous dimensional and electrical measurements; UHV-STM (ultrahigh vacuum – scanning tunneling microscopy) configured with the high-resolution interferometer used to make measured (200 nm to 5 nm) scale samples that can be transferred to other metrology tools.

Solving the advanced metrology needs of the semiconductor industry allows rapid application of nanometer-scale technology into other industrial sectors.

Objective 3:

By FY2007, develop standards and procedures needed for traceable measurements of feature sizes on integrated circuit photomasks composed of binary and/or phase shifting features to improve the accuracy of linewidth measurements in semiconductor manufacturing.

Technical Outputs

FY2003:
Documentation for issuance of SRM 2059.

FY2004:
A publication on the results of an investigation of market feasibility for the development of standards for embedded phase shift photomasks.

FY2005:
A prototype embedded phase shift mask linewidth standard.

FY2006:
A paper published in SPIE that analyzes improvements of photomask metrology through exposure aerial image emulation or alternate technique for all mask types.

FY2007:
A prototype phase shift mask standard; A paper published in SPIE that compares advanced optical techniques for advanced photomask metrology, e.g.: E-beam, Fourier optics, tomography, holography, model image library with islands of tolerance.

Objective 4:

By FY2007, develop and put in place a high accuracy SEM measurement capability, and a set of relevant standard artifacts for dimensional metrology of 100 nm and smaller structures for improving the accuracy of dimensional measurements in nanotechnology and semiconductor manufacturing.

Technical Outputs

FY2003:
Development of new metrology methods to extend the resolution and depth-of-field of production CD SEMs and provide a report to ISMT.

FY2004:
Delivery of calibrated SRM 2090 artifacts to OSRM.

FY2005:
Installation and deployment of new metrology SEM as a main SEM metrology tool.

FY2006:
A NIST-IR publication on the full uncertainty assessment of the new metrology SEM

FY2007:
Delivery of calibrated SEM linewidth SRM 2120 artifacts to OSRM

Objective 5:

By FY2007, complete the design and implementation of an optical-based overlay metrology system for the dissemination of new methodologies, and the calibration and distribution of SRMs for feature overlay on silicon wafers to improve the accuracy of linewidth measurements in semiconductor manufacturing.

Technical Outputs

FY2003:
Prototype overlay wafers available to industry through collaboration with ISMT.

FY2004:
A NIST-IR on the NIST field-of-view optical system mapping and through focus distortion analysis package.

FY2005:
A publication on the results of an improved method for optical system mapping on complex 3-dimensional structures

FY2006:
New reticles for overlay artifacts designed in conjunction with ISMT and a new batch of etched wafers for overlay standards.

FY2007:
Publication on quantified results of the new improved tool configuration and meet the design goal of 1 nm repeatability and 2 nm accuracy in multi-level overlay measurements.

Objective 6:

By FY2007, develop the tools and methodology to enable routine diode laser interferometry measurements and atom-counting to be applied with the UHV-STM on etched silicon features demonstrating sub-nanometer accuracy on artifacts in support of the advancement of nanotechnology

Technical Outputs

FY2003:
Publication on new methods and results for processing and nanofabrication of Si (111) for use in atom-based pitch standards.

FY2004:
The methodology to enable the transfer of samples with sub-nanometer accurate length measurements to other measurement tools such as scanning electron microscopes or atomic force microscopes documented.

FY2005:
Use the new diode laser based interferometry system to measure features with interferometer resolution and accuracy below 0.1 nm and demonstrate this new system in a UHV environment with the new STM system currently being constructed.

FY2006:
Make available to industry as an RM features with less than 5 nm critical dimensions written in atomically flat surfaces on the nanometer and atomic scale.

FY2007:
Measure using the UHV-STM three-dimensional structures of controlled geometry whose dimensions can be measured and traced directly to the intrinsic crystal lattice which are dimensionally stable and allow transfer to other measurement systems.

Anticipated Impacts

Impacts of the NSM program include the development of new measurement methods that, through the ISMT interaction, will be adopted by the semiconductor industry. These methods will result in improved measurement accuracy and repeatability, thereby satisfying one of the prerequisites for the continued shrinkage of circuit minimum feature sizes. Historically, the industry has sought to reduce gate length to reduce capacitance and increase device speed. Success in this endeavor—that is, compliance with Moore's Law—has been well documented for the various generations of microprocessors.

In microprocessor manufacturing, process control through the use of metrology is critical. For a given circuit, each 2 nm shift in manufacturing control results in about 1 ns of speed gain or loss. It is clear that the faster the microprocessor operates, the higher the price (yield is also a concern). (This is evidenced in the 2002 consumer price of an INTEL Pentium® microprocessor; where a 2.4 GH processor was $205 more expensive than a similar 2.2 GH microprocessor.) Ausschnitt and Lagus determined that for 180 nm gates, a 10 nm improvement in the control of the CD is estimated to lead to an increase of $100 in market value per microprocessor. That being the case, the value of the CD control for that generation of microprocessor "exceeds $10 per nanometer." Historically, the implementation of NIST standards and measurement procedures improves the industry's profit. The potential value of this work to the economy is measured in the tens of millions of dollars per year.

Accomplishments of the Past Year

Breakthrough in Sub-10 nm Nanofabrication in Silicon

NIST researchers made a significant breakthrough in the processing and fabrication of atomically flat and ordered silicon surfaces. The researchers have written features of critical dimensions as small as 10 nm in silicon. This process has now been repeated several times and can be considered under control. The recent developments involved the controlled desorption and breaking of hydrogen surface bonds to create stable structures where complex forms and even words can be written in a space of only 100 nm.

Model-Based Linewidth Method Improves Measurement Repeatability

Several scanning electron microscope (SEM) images of a line etched in silicon were analyzed by two standard methods intended to determine the linewidth. The methods were regression to baseline, which is one of several methods that may be used in industrial CD-SEMs, and the model library based method currently being developed at NIST. The scatter in measurement results was more than a factor of three smaller for the new method.

NIST/ISMT Collaborate to Measure New, Fundamental Wafer Targets

NIST and ISMT have completed the first set of preliminary measurements on a new overlay metrology wafer set. The new metrology wafer set, which was designed by NIST in close collaboration with ISMT, IBM, Intel, Motorola and other leading semiconductor manufacturers, has been fabricated in the ISMT fabrication facility in Austin, TX. The wafers have features as small as 180 nm in critical dimension and overlay patterns with offsets as small as 5 nm.

ISMT Reports Completed Early

The two ISMT contracts were completed early. The final report were submitted on “Trial Shape-Sensitive Linewidth Measurement System” and “Application of Nano-tips to Production CD-SEMs.” Both of these contracts are involved with NIST involvement in the improvement in critical dimension metrology in the semiconductor production environment.

Scanned Probe Oxidation Given Unique Recognition

Scanned probe oxidation, pioneered several years ago by PED, has been given its own unique code, 81.16.Pr, in the recently updated American Institute of Physics PACS (Physics and Astronomy Classification Scheme) database. Since the first report appeared in a paper entitled “Modification of hydrogen-passivated silicon by a scanning tunneling microscope in air” by J. A. Dagata, J. Schneir, H. H. Harary, C. J. Evans, M. T. Postek, and J. Bennett, Appl. Phys. Lett 56 2001 (1990), it has become the most widely used nanofabrication technique based on the scanned probe microscope.

NIST Researchers publish significant improvement in overlay reversal methodology

This methodology enabled the NIST researchers to provide quantitative information on the optical tool asymmetries and on sample asymmetry. This is the first time that accurate information on the quantitative effects of asymmetry can be applied to overlay metrology. This method has enabled the overlay team to put complete uncertainties on the measurements with complete expanded uncertainties of less than 2 nm.

NIST/ISMT distribute overlay wafers with the first complete expanded uncertainties

NIST and ISMT worked closely to design, fabricate and release two versions of overlay test wafers for use by the semiconductor industry and instrument manufacturers. The first version is an inexpensive un-calibrated version used for instrument testing and set-up and the second is a NIST certified version for instrument calibration. This marks the first measurements with a full uncertainty statement and complete traceability chain from the NIST overlay metrology tools on wafers measured around the World.

High Pressure SEM Data on Photomasks

The ITRS Roadmap targets specimen charging in the SEM as a difficult problem and alternate solutions should be sought. To that end, NIST was invited to present two talks to the ISMT AMAG and the MASC highlighting new data obtained through NIST collaboration with FEI Co. (now Veeco) and additional paper was presented at the SPIE Photomask Meeting (BACUS). This work applied high-pressure (environmental) microscope technology to photomasks inspection and metrology. This work demonstrated that specimen charging can be neutralized utilizing this technology. The presentations culminated several years of personal interaction with then Electroscan and now FEI Co. in applying this technology to photomask and semiconductor metrology.

Additional FY2002 Accomplishments

- Published 25+ publications;
- For OSRM, delivered calibrated SRM 2059 optical photomask linewidth artifacts; Prepared and measured 5 completed 2-D grid reticles;and SRM 2800 microscope magnification standard certificate approved.
- Developed new computer controlled nano-tip making process.
- Designed and fabricated microfluidic devices and embossed PVC films.
- Completed the first international overlay measurement comparison.
- Designed and fabricated a 0.1 micrometer optical mask for combinatorial thin film research.
- Developed and tested the maskless optical lithography exposure system.
- Applied new high vacuum/environmental SEM techniques to photomask metrology and presented to ISMT AMAG, MASC and SPIE Photomask Metrology (BACUS).
- Gave invited presentations at: European Nanotechnology Conference; CENSTAR/VAMAS Workshop at NPL, England; Nanofabrication and Nanometrology meeting, Tokyo; Ramon Areces Foundation, Madrid; SPIE Nanotechnology of Polymeric Smart Materials Workshop
- Completed several imaging and measurement data runs on the Geller MRS-4 sample with M^3.
- Calibrated 21 high precision length standards with the LSI.
- RM 8091 introduced to the microscope community as a sharpness standard.
- Installed a revised high-performance SEM stage for the Hitachi 4700 developed in collaboration with E. Fjeld Company.
- Demonstrated to ISMT and SPIE Microlithography that model-based linewidth methodology improves SEM precision by a factor of 3.
- First photomask using phase shifting features designed for optical fabrication of SRM 2090.
- Acquired and installed Nikon X-Y 5; optical metrology instrument from Photnonics

Workshops

- Workshop on Nanostructure Science, Metrology and Technology (Workshop Proceedings available through SPIE)
- Participated in three ISMT Metrology Council workshops
- Participated in two ISMT MASC Workshops

Other Information

Short Course: CD Metrology and Image Formation in the Scanning Electron Microscope. SPIE (with Dr. Oliver Wells). SPIE Microlithography Meeting, Santa Clara California, March 2002

Patent Number 5,857,258 - Electrical Test Structure and Method for Measuring the Relative Locations of Conductive Features on an Insulating Substrate

Patent Number 5,920,067 - Monocrystalline Test and Reference Structures, and Use for Calibrating Instruments

Crystal Award of Excellence

R&D 100 [SEM Monitor]

2002 SPIE Microlithography Symposium Chair
Participants in ITRS committee on CD metrology

Standards Participation

- American Society for Testing and Materials (ASTM) E42 Surface Analysis
- ASTM F1 Electronics
- Semiconductor Equipment and Material International (SEM)I Standards - Microlithography
- 2-D Grids (Chair)
- SEMI Standards P35 task force (Chair) Metrology Terms in Microlithography
- SEMI Standards Metrics Committee
- SEMI Standards - Microlithography - Electrical Test Structures
- SEMI Standards - Microlithography - EUVL Mask
- SEMI Standards - Microlithography - Next Gen. Photomask
- SEMI Standards - Microlithography - Overlay Targets (Chair)
- SEMI Standards - Microlithography Global Metrology
- ISO TC 202/WG3

Measurement Services

Calibrations

- Linescale Interferometer Calibration of length scales

Special Tests

- 2D grids and Overlay Measurements (internal)

SRMs

- SRM 2800 – New Optical Microscope micrometer
- SRM 2059 – New Photomask Linewidth (in process)
- SRM 2120/RM 8120 – SEM Linewidth (in process)
- SRM 2090/RM 2090 – SEM magnification
- SRM 2091/RM 8091 – SEM Sharpness
- SRM 5000 – Optical Overlay
- SRM 5001- 2D Grids – (in process)

PREDICTIVE PROCESS ENGINEERING

Program Manager:
Kevin Jurrens

FTEs:	9.5
Program Funding:	$1728 K

FY2003 Projects

- Process Specification Language (PSL)
- Process Integration Framework
- Metrology for High Speed Machining
- Assessment of Machining Models (AMM)
- Materials Data and Metrology for Machining Simulation
- Material and Machining Knowledge Integration to Achieve First Part Correct
- Model-Based Control for Process Optimization

Program Goal

By 2005, support the industry need for "first part correct" manufacturing by establishing an industry-accepted and widely adopted integration framework for sharing predictive knowledge about machining processes and resources with engineering and control systems using a standard semantic-based process representation and validated physics-based models for milling and turning.

Customer Need

Annual U.S. expenditures on machining operations total more than $200 billion, or about 2 percent of the Gross Domestic Product (GDP). Total expenditures on all mechanical manufacturing processes, including forming and stamping, are substantially higher. Manufacturing processes are inherently complex; as a result, process development is often ad hoc and empirical. Process parameters, such as machining speeds, feed rates, and tool selection, are typically chosen by costly, trial-and-error prototyping, with the result that solutions are often sub-optimal. A survey by the Kennametal Corporation dramatically demonstrates this in its findings that U.S. industry chooses the correct tool less than 50 percent of the time, uses cutting tools at their rated cutting speed only 58 percent of the time, and uses cutting tools to their full life capability only 38 percent of the time. These sub-optimal practices are estimated to cost U.S. industry $10 billion per year. Pressure from international competitors is driving U.S. industry to seek more sophisticated and cost-effective means of choosing process parameters through modeling and simulation. Optimal manufacturing performance requires a solid understanding of the impact of individual parameters on the various levels of the control hierarchy, from the shop floor to the overall enterprise.

A principal barrier to reducing inefficiencies is the lack of access to validated, physics-based models of the manufacturing processes when key engineering decisions are made. Although there has been significant progress in the predictive simulation of low-strain-rate manufacturing processes such as forming, rolling, and drawing, there is a need for better predictive capabilities for high-strain-rate processes such as machining. The state of the art in predictive modeling of machining operations is severely limited because measurement and materials characterization capabilities are lagging model development. In other words, current models give impressive qualitative results, but there are virtually no data with which to validate these results. Without focused metrology efforts to understand and characterize the processes fully, it is likely that industry will lose faith in machining models.

A second barrier to reducing manufacturing process inefficiencies is the lack of simple mechanisms to enable the exchange of process information among manufacturing systems. Market analysts at Gartner Group Inc. estimate the costs associated with the exchange of process information among manufacturing applications in U.S. industry at approximately $2 billion per year. The development of standards and methodologies to provide a rigorous foundation for representation, exchange, and integration of process-related data could reduce costs by an estimated 15 to 20 percent , which translates into a savings of $300 million to $400 million per year. U.S. manufacturers and industry groups identified these problem areas through numerous public forums and publications. In particular, the 1998 Integrated Manufacturing Technology Roadmap (IMTR)[1] identified a number of industry priorities and critical capabilities that provide direct support for this program. Specifically, the IMTR identifies science-based manufacturing, first part correct, intelligent process advisors, and robust process models as key industry needs.

Technical Approach

The vision of "first part correct" demands a different approach in many areas of manufacturing engineering. A shift is required from classical feedback quality assurance and optimization, to model-based feed-forward process design and quality control. This program will build the foundation to enable a new paradigm for predictive process engineering and science-based manufacturing.

This foundation will be built upon a science-based understanding of material removal manufacturing processes, advanced process metrology methods, validated analytical models to predict process performance and optimize manufacturing decisions, and rigorously defined representations for manufacturing process information. Process metrology methods will provide new understanding and data for process characterization to develop and improve the predictive model, process specification, and manufacturing process itself. Product and process designers will have knowledge of and access to process specifications, manufacturing knowledge, and predictive process models to generate product and process designs seamlessly to produce the correct part the first time.

To meet the needs, a number of areas must be addressed in parallel. Specific activities in each area will be adapted to take advantage of collaborations with industry, academia, and international organizations. These collaborations will inform and guide program efforts throughout the course of the work to ensure the usability and applicability of the program outputs. Key technical areas are:

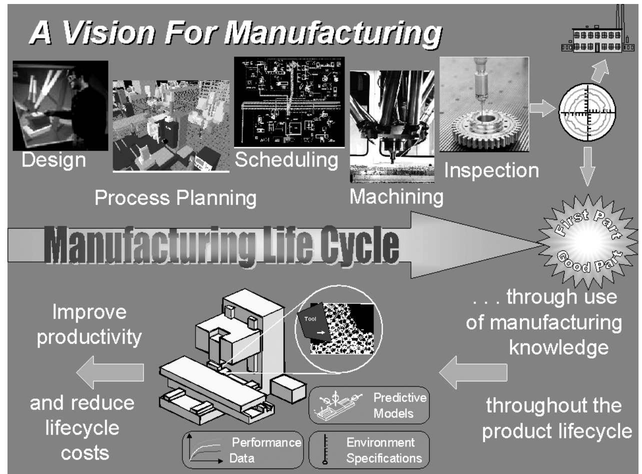
- Development of measurement methods to provide in-situ, real-time, or process intermittent information about milling and turning material removal processes

[1] Now maintained by the Integrated Manufacturing Technology Initiative [IMTI]. http://imti21.org

This program will address process metrology topics such as machine dynamics, thermal measurements during material removal, dynamic material response, and experimental data to evaluate models of material removal processes. Related measurement methods and measured quantities will also be addressed. A specific program emphasis will be development of appropriate methods to generate materials response data under the high temperature and high strain rate conditions needed for simulation of machining operations. The absence of this materials characterization data and an appropriate materials model represents a major limiting factor in the modeling of machining processes.

- Based on the process metrology methods and resulting experimental data, development and validation of physics-based models of milling and turning processes to support next-generation industry priorities in product and process design, manufacturing planning and optimization, and machine control

With the increased understanding of machining processes, the program will extend and/or validate the capability of existing physics-based models of milling and turning processes. While new process model formulations will be developed when necessary, the primary focus will be modification or extension of existing models to account for new information about temperatures, forces, machine dynamics, tool wear, material properties, and other factors. Program activities will include the evaluation and application of such techniques as receptance coupling to predict the dynamic behavior of systems based on the performance of individual sub-systems. Resulting process models will be used to predict process behavior and to establish optimum cutting parameters for sample applications. A key program element will be validation of machining process models using empirical data to give confidence in the performance of the model, both within and external to the regimes of "known" data. The validated process model will allow the ability to understand and predict the effect of parameter changes for situations that are outside the currently available empirical data.



Program results will demonstrate an integrated, model-based approach for making predictive knowledge about manufacturing processes accessible when key decisions are made.

- Development of standard representations for manufacturing process information, standard interfaces among applications, and standard integration methods to enable seamless integration and data interoperability for process-related applications

The program will address the challenge of system interoperability by developing a standard, rigorously defined data representation for manufacturing process information. Through development, prototype implementation, and standardization of the Process Specification Language (PSL), the program will create an exchange language that allows for the representation of all relevant manufacturing process information independent of any specific application and that defines unambiguous and rigorous semantics for the concepts being represented. The NIST PSL project results have been recognized and accepted as the basis for the international standard ISO 18629 currently being developed. The PSL consists of a modular, extensible data model that captures the concepts required for process specification. The data representations and integration methods will provide necessary components to enable complete use of manufacturing knowledge and process-related data throughout the product lifecycle.

- Development and demonstration of methods for effectively using predictive process models for product and process design, manufacturing planning and optimization, and machine control

To emphasize and demonstrate integration of the various project components, the program will direct specific efforts to implementing the standard process representations and predictive models to address typical industry challenges. In general, the process metrology activities will provide new understanding and data to improve the process modeling activities; the process data representation and interoperability activities will combine with the process modeling activities to enable application to industry problems and demonstration scenarios. The program will design and implement a prototype process integration framework to share manufacturing process knowledge with engineering and control systems. This framework will provide a demonstration forum to validate program outputs and ensure sufficient usability and functionality of results. The program will also implement results through external collaboration in the area of model-based control. This collaboration will provide the application focus, sample user part, and typical manufacturing challenges to evaluate program results and promote the concepts of predictive process engineering.

Program Objectives and Technical Outputs

Objective 1:

By FY2003, gain further industry support and participation through site visits, workshops, and collaborations to obtain feedback on the program content, validate and transfer program results, and establish future program directions.

Technical Outputs

FY2003:

Participation in the NIST Smart Machine Tools Workshop in December 2002; Participation in the CIRP Workshop on Modeling of Machining Operations in May 2003; and Program presentations provided to industry visitors to NIST.

Objective 2:

By FY2004, establish and document in archival engineering journals a suite of measurement and validation test methods providing in-situ, real-time, or process-intermittent information about milling and turning processes to enable development and validation of highly-accurate process models.

Technical Outputs

FY2003:

Publication of research results in dynamic material response, thermal measurements of machining, machining process dynamics for thin-walled workpieces and Navy propulsion system components, and surface location errors during milling; Publication of machining process metrology methods and results for the U.S. Army turning center; Demonstration of the NIST Pulse Heated Kolsky Bar apparatus integrated with the rapid heating system; and Demonstration of improved material characterization and machining simulation capabilities based on Kolsky bar project results.

FY2004:
Publication of comprehensive guide to the state-of-the-art in manufacturing process metrology to address measurements and relationships among forces, temperatures, tool wear, workpieces, vibration, materials properties, and related factors.

Objective 3:

By FY2005, establish and document a publicly available set of validated, physics-based models of milling and turning processes to support next generation industrial priorities in planning, analysis, optimization, and real-time control.

Technical Outputs

FY2003:
Publication of process model evaluations based on comparison of predictions submitted for the Assessment of Machining Models (AMM) effort with validation data; and Demonstrated integration of material transformation knowledge and machining process knowledge resulting in improved process models.

FY2004:
Publication of survey on state-of-the-art of process model availability and capability; Publication of generalized methodology for process model validation; and Publication of validation reports for milling and turning models.

FY2005:
Publication of comprehensive guide to the state-of-the-art in manufacturing process modeling for milling and turning operations to address the areas of model availability, accuracy, functionality, applicability, and usability.

Objective 4:

By FY2005, establish published designs, functional software tools, and working draft standards for a suite of rigorously-defined representations for manufacturing process information based on first principles and the methods for mapping manufacturing process data based on its underlying semantics to enable unambiguous integration of process-related applications for extended enterprises.

Technical Outputs

FY2003:
Submission of ISO 18629 Part 41 Activity Extensions and Part 42 State and Time Extensions for Committee Draft (CD) balloting; Demonstration of process information exchange protocols for two manufacturing applications; Implementation of the PSL Twenty Questions Semantic Mapping Tool.

FY2004:
Publication of product and machine ontologies; Specification of process information exchange protocols to support self-integrating systems; and Submission of ISO 18629 Part 13 Duration and Ordering Theories and Part 43 Activity Ordering and Duration Extensions for committee draft balloting.

FY2005:
Publication of PSL agent theories and business-to-business ontologies; and Development of working drafts for remaining ISO 18629 Parts.

Objective 5:

By FY2005, develop and conduct a series of annual demonstrations of the process integration framework to showcase the current status and capability and to illustrate the usefulness and value of incorporating predictive process models to improve the applications of design, analysis, planning, optimization, and real-time control.

Technical Outputs

FY2003:
Publication on concepts and status of process integration framework; Publication on data and interface requirements for model-based control; and Demonstration of Phase 3 process integration framework.

FY2004:
Demonstration of Phase 4 process integration framework; Demonstration of integrated models for manufacturing knowledge representation (material, equipment, and process) incorporated into the process integration framework; and Demonstration of model-based control using predictive process models.

FY2005:
Demonstration of Phase 5 process integration framework; and Demonstration of successful machining of a complex, thin-walled aluminum workpiece to predicted tolerances with minimal known part distortion, subsurface damage, and residual stresses.

Anticipated Impacts

This program will have positive impacts on the manufacturing community by 1) enabling system interoperability for manufacturing process information; 2) creating a recognized integration framework for sharing process knowledge; 3) increasing the quality of predictive process models due to validation efforts; 4) increasing industry confidence in and usage of predictive process models; 5) increasing typical industry material removal rates for milling and turning due to use of predictive models for process dynamics; and 6) reducing workpiece scrap and decreasing process downtime for milling and turning due to use of predictive models for tool wear and tool life.

Accomplishments of the Past Year

Staff Recognition

Rob Ivester was awarded the 2002 Serope Serope Kalpakjian Outstanding Young Manufacturing Engineer Award by the Society of Manufacturing Engineers (SME) in recognition of his significant achievements and leadership in the field of manufacturing engineering.

Milestones Achieved in PSL Development

Standardization of the Process Specification Language (PSL) as ISO 18629 achieved the following milestones this year: Part 1 (Overview and Basic Principles) was submitted for Draft International Standard (DIS) balloting; and Part 11 (PSL-Core) and Part 12 (Outer Core) were submitted for Committee Draft (CD) balloting. Version 2.0 of PSL was released by NIST to revise and add to the existing extensions and to incorporate grammars for process descriptions for activities and occurrences in the different classes of the ontology.

AMM Calibration Data Released

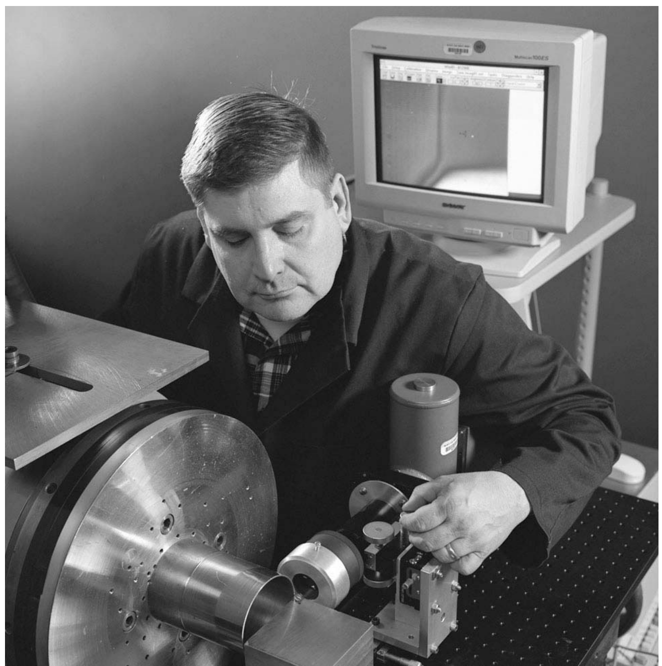
The Assessment of Machining Models (AMM) project completed and released the full set of calibration data for forces, temperatures, and cutting tool wear to enable an unbiased evaluation of the current state of predictive modeling of machining. Based on this calibration data, predictions are solicited from the process modeling community for a similar set of conditions. These predictions will be compared with a validation data set generated by NIST, Ford, General Motors, and Caterpillar through controlled machining experiments.

Kolsky Bar Milestones Reached

The NIST Pulse Heated Kolsky Bar apparatus was constructed and tested for obtaining stress-strain relationships of material samples. Materials data was obtained in April for samples of AISI 1045 steel at room temperature. Further tests with annealed copper samples in June confirmed the high strain rate capability through a positive comparison with existing external data. The rapid heating capability was implemented and heating experiments in August confirmed that steel samples could achieve desired temperatures in the range of 500° C to 700° C.

Machining Productivity Increased for U.S. Navy

Tony Schmitz contributed to joint efforts with the Naval Surface Warfare Center and other collaborators to study and implement high-speed machining techniques for the production of Navy propulsion system components. Through improved understanding of the process dynamics and optimization of process parameters for machining the nickel-aluminum-bronze material, NIST results achieved a 10X increase in material removal rate. The objective is to reduce the production time for a submarine propeller (roughly 6 meters in diameter and 2 meters deep) from twelve months down to four months.



Measuring temperature distribution at the tool/workpiece interface helps develop and validate mathematical models of the cutting process.

PSL Tools Developed

Michael Gruninger and Cyrille Brustlein completed initial versions of the Twenty Questions Semantic Mapping Tool and the Translator Generator Tool to assist software developers in the semantic and syntactic translations, respectively, for use of the ISO 18629 Process Specification Language (PSL) specifications.

Collaboration Formed With U.S. Army

With support from the Totally Integrated Munitions Enterprise (TIME) program, NIST and the U.S. Army Picatinny Arsenal initiated collaboration in the area of model-based control and development of a technology testbed for the U.S. Army to implement and evaluate advanced manufacturing techniques. This collaboration includes NIST programmatic activities in machine tool metrology, machining process metrology, and open architecture control for a new turning center application to be developed at Picatinny Arsenal.

New ATP Project Initiated

Intramural funding from the NIST Advanced Technology Program (ATP) was awarded to conduct a three-year effort titled "Material and Machining Knowledge Integration to Achieve First Part Correct." Project participants from across NIST will develop an integrated capability for representing knowledge about material properties, machine tool performance, and machining processes.

Results will be demonstrated through improved capability for machining complex, thin-walled aluminum workpieces.

Surface Location Errors Studied to Improve Machining Accuracy

Tony Schmitz, Hans Soons, and Brian Dutterer completed the first phase of a study on surface location errors in high-speed milling. These errors occur due to the flexibility in the workpiece/cutting tool/spindle/machine tool system. The errors are determined by the instantaneous tool deflection when producing the finished surface, which in turn is determined by the relationship between the system natural frequency and the forcing frequency, or spindle speed. Experimental results showed surface location error amplitudes larger than the more generally modeled and compensated geometric and thermal machine tool errors, even during low radial immersion cutting conditions such as might be used for traditional finishing.

Thermal Measurement Uncertainties Reduced

Rob Ivester and Eric Whitenton developed a system for high-speed, simultaneous capture of visible and infrared (thermal) images during orthogonal machining. Images were recorded during cutting experiments with 7075 aluminum. The images were compensated for the camera nonuniformity and converted to temperatures using emissivity measurements and calibration data from use of a blackbody source. These results greatly reduce the uncertainties for measurement of cutting temperatures for the machining of aluminum.

Phase 2 of Integration Framework Demonstrated

Kevin Jurrens, Shaw Feng, and Keith Stouffer presented a review of the FY2002 activities and progress of the Process Integration Framework project and demonstrated the Phase 2 status and capability. The demonstration built upon the results from the prior year by expanding the functionality of the Process Planning perspective to include tool material selection and tool life modeling, adding the Manufacturing Control perspective, and incorporating several new software agents and capabilities. This effort serves as the key integration mechanism for the project components of the PPE Program.

Visits to NIST

PPE Program staff hosted or participated in several visits to NIST, including representatives from Chrysler, Boeing, U.S. Army Picatinny Arsenal, Naval Surface Warfare Center, National Defense University Industrial College of the Armed Forces, Lamb Technicon, Third Wave Systems, Joint Defense Manufacturing Technology Program (JDMTP) Advanced Manufacturing Enterprise (AME), University of North Carolina at Charlotte, Department of Energy Interagency Manufacturing Operations Group, Finland Technology Program for Mechanical Engineering (MASINA), Institute for Defense Analysis, Washington University (St. Louis), Southern University, Auburn University, Knowledge Based Systems Inc., Purdue School of Technology, University of Maryland, Central Manufacturing Technology Institute of the Indian Department of Commerce and Industry, and the National Institute of Applied Sciences (INSA) of Lyon, France.

Workshops

Rob Ivester and Kevin Jurrens participated in the 5th CIRP International Workshop on Modeling of Machining Operations in West Lafayette, IN in May 2002. Rob presented an overview of the AMM project and described the structure and content of the AMM calibration data set.

During FY2003, program staff will contribute to the NIST Smart Machine Tools Workshop in December 2002 and the CIRP Workshop on Modeling of Machining Operations in May 2003.

Standards Participation

- ISO TC184/SC4/JWG8 Manufacturing Process and Management Information
  - Program staff lead the standardization of the Process Specification Language (PSL) as ISO 18629.
- ISO TC184/SC5/WG4 Manufacturing Programming Environments
  - Program results have been incorporated in ISO 16100 (Manufacturing Software Capability Profiling and Interoperability), Part 1 (Framework for Interoperability) and Part 2 (Information Models for Interoperability).
- ISO/IEC JTC1 Information Technology / SC32 Data Management and Interchange
  - Program staff serve as Project Editor for the Knowledge Interchange Format (KIF) standard.
- Foundation for Intelligent Physical Agents (FIPA)
  - Program staff interact with the FIPA Ontologies Technical Committee, Semantics Technical Committee, and the Planning and Scheduling Special Interest Group to maintain awareness of the current status and future direction of FIPA standards and to ensure that program results conform to FIPA specifications.

Program Manager
Ram D. Sriram

FTEs:	9
Program Funding:	$1077 K

2003 Projects

- Parametrics Exchange
- Assembly and Tolerance Representation
- Design-Analysis Integration
- Heterogeneous Material Representation
- Knowledge Representation for Next-Generation CAD

PRODUCT ENGINEERING

Program Goal

Establish a semantically-based, validated, product representation scheme as a standard that supports the seamless interoperability among current and next generation computer-aided design systems (CAD) and between CAD and other systems that generate and use product data, to help the manufacturing industry achieve a 10 percent reduction in interoperability costs and a tenfold improvement in design exploration capability.

Customer Needs

According to a Daratech report[1], CAD, computer-aided manufacturing (CAM) and computer-aided engineering (CAE) constitute an industry valued at approximately a $6.5 billion per year. With emerging areas, such as immersive CAD and knowledge-based CAD, the value of this industry is likely to increase considerably in the next decade. A major problem with the emergence of various heterogeneous CAD systems is the lack of interoperability among these systems. A 1999 study by RTI International[2] estimated that imperfect interoperability imposes costs of at least $1 billion per year on the U.S. automotive supply chain alone; other industries are in similar predicaments. This problem has significant implications for the costs at all design stages, and over all product cost, because decisions made during the design stage determine 70 percent of a product's cost over its life.

To assess the importance of various CAD/CAM/CAE technologies to industry, as well as to identify specific interoperability needs, several workshops have been sponsored by NIST.[3]

Each of these workshops was attended by dozens of practitioners and researchers from large and small businesses, government, and academia, representing the country's leading engineering organizations, software vendors, and academic institutions. Participants clearly underscored the need for interoperability standards and knowledge representation schemes.

In addition, a number of documents identify critical industry needs in this area.[4]

[1] http://www.daratech.com/

[2] http://www.rti.org

Technical Approach

The program focuses on the key issues emerging from the new collaborative product development paradigm. Specifically, the primary needs for the next generation of CAD/CAM/CAE software systems are interoperability among software tools; collaboration among distributed designers and design teams; integration of data and knowledge across the product development cycle (from design to analysis to manufacturing and beyond); as well as knowledge capture, exchange and reuse. This program's activities and efforts range from specification and standards development to technology development and prototype implementation. The program is intended to provide the foundation that will support the creation of next-generation product development tools, thereby increasing the efficiency, effectiveness, capability, and productivity of U.S. industry.

ISO 10303, or the STandard for the Exchange of Product model data—informally known as STEP—is capable of successfully transferring product shape models in terms of their geometry and topology. However, modern CAD systems generate models containing additional information concerned with parametric representation, constraints and features. This permits a shape model to be edited or optimized according to the designer's original notions. It is highly desirable that STEP be extended to capture and transmit this additional information, to make it easier to edit models following a transfer. The Parametrics project currently works towards this goal, with the aim of saving the time currently spent in trying to regenerate information that was present in the transmitted model but lost in translation into the STEP format. The result will be improved efficiency in the product development cycle.

A major concern with current CAD tools is a lack of standardized representations for some types of assembly data, such as inter-part relationships, mating features, and others. Such representations will enable more efficient and cost-effective integration of assembly analysis tools, and more accurate translations of data. It is expected that work on assembly modeling and representation will provide input to the incorporation of assembly information content into STEP.

In addition, the program is developing methods and best practices for tolerance analysis and synthesis. The aim of this work is to advance the use of tolerance information to the earliest possible stages of design, in contrast to the traditional post-design approach of performing tolerance synthesis after design. This, in turn, requires effective representation of tolerance information during various stages of design such as during assembly modeling.

One of the serious current interoperability gaps occurs between CAD design tools and CAE analysis tools. The design-analysis integration project has pragmatic and conceptual components. On the pragmatic side, we are collaborating with the TIDE (Technology Insertion Demonstration Experiment) program of the Software Engineering Institute (SEI)

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[3] These include: Standard for the Exchange of Product Model data (STEP)-based Solid Interchange Format Workshop (November 1996): NIST Design Repository Workshop (November, 1996): Network-Centric CAD: A Research Planning Workshop (December, 1996): Tools and Technologies for Distributed and Collaborative Design (August, 1997): Assembly Level Tolerancing: Standards and Implementation Issues Workshop (April 1997): Knowledge-based Systems Interoperability Workshop (November, 1997): Intelligent and Distributed CAD Workshop (July, 1998): Design Manufacturing Integration Workshop (November 1998): and Virtual Assembly Technology Meeting (March 1999).

[4] These include: Manufacturing Infrastructure: Enabling the Nation's Manufacturing Capacity (Committee on Technological Innovation, National Science and Technology Council): Collaborative Virtual Prototyping Sector Study (study sponsored by the U.S. Navy, study performed by the North American Technology and Industrial Base Organization): Integrated Manufacturing Technology Roadmap (government-funded technology roadmap): Information Technology for Manufacturing: A Research Agenda (from the Committee to Study Information Technology and Manufacturing, National Research Council, National Academy Press, 1995): General Electric (GE) Pilot Project Case Study Report (GE case study sponsored by Defense Advanced Research Projects Agency (DARPA)): Visionary Manufacturing Challenges for 2020 (Committee on Visionary Manufacturing Challenges, National Research Council, National Academy Press, 1998): Advanced Engineering Environments (Committee on Advanced Engineering Environments, Aeronautics and Space Engineering Board, National Research Council, National Academy Press 1999, 2000), and others.

at Carnegie Mellon University in improving CAD-CAE interoperability for small defense contractors. Our task is to provide guidance in the implementation of a pilot technology program and to extract generalizations from the TIDE results. On the conceptual side, we are defining a data architecture consisting of a common master model and a number of discipline-specific aspect models, treating the spatial CAD model as just another aspect model in parallel with discipline-specific analysis models (e.g., those supporting strength, thermal, and flow analysis). A number of organizing principles for the master model and implementation principles for a potential system are being investigated.

Layered Manufacturing (LM), also known as solid freeform fabrication (SFF), or rapid prototyping (RP), is an additive manufacturing process in which the objects are constructed layer by layer. Considerable progress has been made in the last decade and it is now possible to produce multi-material objects, with functionally graded material, in LM machines. Where as the LM technology is progressing ahead, the mechanism of transferring the data from a CAD system to LM system has remained unchanged. The de-facto industry standard, Stereolithography (STL) file format, whose format consists of a mesh of connected three-dimensional triangles that represent the part shape. One of the major deficiencies in the STL format is the inability to represent heterogeneous material. In this research we propose to work towards the development of a representation scheme that would address this and other deficiencies in STL and enable advanced capabilities from next-generation manufacturing systems. Our approach would build upon several primitives available in STEP ISO 10303. In addition, we will strive toward the development of a theoretical framework for dealing with the representation of heterogeneous material.

In the area of knowledge representation for next-generation CAD, one project is working toward the development of an information modeling framework to support the creation of design repositories, the next generation of design databases, which would facilitate knowledge-aided e-commerce. This project is driven by industry needs for technology to support the increasing role of knowledge-based design, including the representation, capture, sharing, and reuse of corporate design knowledge. A second project deals with the development of a core product representation—-called the Core Product Model (CPM)—-and semantic foundations that support the long term objective of self integrating systems.

Program Objectives and Technical Outputs

Objective 1:

By FY2003, develop STEP resource on parameterization and geometric constraints to Draft International Standard (DIS) level.

Technical Output

FY2003:
Parametrics Exchange: DIS version of ISO 10303 Part 108 document.

Objective 2:

By FY2003, develop case studies to demonstrate the proposed assembly and tolerance information model, with specific focus on tolerance analysis and synthesis.

Technical Output

FY2003:
Assembly and Tolerance Representation: Proposed model included in proposed ISO 10303 Part 44 and Part 109.

Objective 3:

By FY2003, develop and publish an information-modeling framework based on a semantically rich master product model for the support of all design and analysis activities throughout the design lifecycle of an artifact.

Technical Output

FY2003:
Design-Analysis Integration: Report describing information modeling framework with potential organizing and implementation principles.

Objective 4:

By FY 2003, perform computational experiments to study feasibility of the material-solid modeling using distance fields in common engineering situations.

Technical Output

FY2003:
Heterogeneous Material Representation: Report detailing the ingredients of the proposed representation scheme and analysis of how these maybe incorporated within ISO standards.

Objective 5:

By FY2003, develop formal computer interpretable representations for archiving and retrieving information flow in design.

Technical Output

FY2003:
Knowledge Representation for Next Generation CAD: Document describing an object-based representation that can define the intended behavior of devices.

Objective 6:

By FY2004, work toward standardization of the Universal Modeling Language (UML) models for assembly and tolerance representation with ISO 10303 SC4/WG12 and work with American Society of Mechanical Engineers (ASME) Y14.5.M-200X on proposed revision of ASME Y14.5M-1994 (R 1999) to include assembly level tolerance standards.

Technical Output

FY2004:
Assembly and Tolerance Representation: Report describing the use of the proposed assembly and tolerance representation in the harmonization of ASME and ISO efforts.

Objective 7:

By FY2004, develop and publish an elaborated version of an information modeling framework based on further research, feedback from industry and standardization organizations.

Technical Output

FY2004:
Design-Analysis Integration: Report and technical presentations of elaborated framework.

Objective 8:

By FY2004, propose specific data structures and algorithms for incorporating the new technology within existing CAD systems.

Technical Output

FY2004:
Heterogeneous Material Representation: Prototype system demonstrating the developed capabilities and a report summarizing the developed techniques and algorithms.

Objective 9:

By FY2004, develop a logic-based representation scheme that can be used for verifying intended behaviors.

Technical Output

FY2004:
Knowledge Representation for Next Generation CAD: Report describing the logic-based approach and a prototype demonstrating the proposed approach.

Objective 10:

By FY2005, formalize the proposed assembly and tolerance representations into an ontological framework to achieve semantic interoperability.

Technical Output

FY2005: Assembly and Tolerance Representation: Publications describing the ontological framework and appropriate ISO/ASME documents.

Objective 11:

By FY2005, demonstrate non-trivial applications of the new proposed representation and technology in the context of design and/or manufacturing applications, including engineering analysis and/or planning.

Technical Output

FY2005:
Heterogeneous Material Representation: Report summarizing capabilities of the developed technology, future directions, and open issues.

Objective 12:

By FY2005, diffuse the proposed knowledge representation scheme to the industry and various standards organizations, including demonstration of knowledge-level interoperability.

Technical Output

FY2005:
Knowledge Representation for Next Generation CAD Prototype demonstrating knowledge-level interoperability between two CAD systems and associated publications.

Objective 13:

By FY2005, develop a five-year plan for future work in the Product Engineering Program.

Technical Output

FY2005:
Roadmap Document: A document describing the roadmap for future Product Engineering Research.

Anticipated Impacts

Anticipated impacts include improved infrastructures for using and exchanging design knowledge, and for the seamless integration of design and production information across time, space and engineering domains. These benefits will translate to broad-based economic benefits through accelerated product development, reduced direct design costs, and improved product quality. For example, we expect to see:

1. Enhanced knowledge-aided electronic commerce for supporting intelligent and distributed design. Access to distributed design databases and seamless interoperability among CAD systems would result in an efficient electronic commerce framework.
2. Increased competitiveness of U.S. industry by reducing design and production costs as well as product development time. Specific program targets include: reduction in direct design costs of 10 percent to 30 percent, reduction of time-to-

market of 25 percent to 75 percent, and reduction of defect rates and engineering change requests of 23 percent to 70 percent.

3. Increased capture and linkage of design information across various stages of the product life cycle. Benefits will include improved reuse of design information across product families, and more rapid redesign efforts. In addition to reducing development time, improved feedback of knowledge into subsequent design processes will increase quality and reduce warranty and repair costs later on.
4. Better interoperability through use of formal semantics. Traditionally, interoperability is achieved without explicit exchange of semantic information by agreeing on semantics prior to definitions of standards and exchange mechanisms. The addition of ontological information-to-information exchange, enabling semantic interoperability, is a key stage along the path toward self-describing and ultimately self-integrating systems.

Accomplishments of the Past Year

Parametrics

ISO 10303-108 (Parameterization and constraints for explicit geometric product models) — has passed Committee Draft (CD) ballot; DIS version is in preparation.

New resource, so far unnumbered (Procedural and hybrid representation) – submitted for a joint New Work Item proposal and CD ballot. This resource will provide basic mechanisms for construction history modeling.

Assembly and Tolerance Representation

A draft version of an assembly/tolerance model using UML was completed.

ISO's proposed assembly representation (ISO Part 109) and NIST assembly model were thoroughly discussed at a recent ISO meeting and subsequently at Nihon Unisys Headquarters with the Japanese National Committee.

Participated in the VATC (Virtual Assembly Technology Consortium) meeting. VATC is an industry-university-government consortium that aims to demonstrate immersive CAD applications and to develop open standards for integrating traditional CAD and immersive CAD systems.

Sudarsan Rachuri gave the keynote address at ASPE (American Society of Precision Engineers) Summer Topical Meeting on Tolerance Modeling and Analysis (Charlotte, NC, July 15-16, 2002). He gave an invited presentation entitled "Information models for Design Tolerancing of Electro mechanical Assemblies."

Design-Analysis Integration

Developed a hierarchical, multi-aspect information architecture, with a Master Model containing shared information and functional models acting as views on the Master Model.

Wrote several technical reports for the TIDE program of the Software Engineering Institute at Carnegie Mellon University.

Knowledge Representation for Next Generation CAD

Simon Szykman gave the Keynote Address on the NIST Design Repository Project, at an organized event on the topic of knowledge management ("Creating Value from Knowledge Assets") sponsored by the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center's Goddard Library.

Completed the design rationale extensions to the NIST Core Product Model.

Extended distributed web-based architecture implementation.

Expanded design repository database and interfaces to allow for inclusion of catalog design data.

Developed tools to aid in creation and population of organized component catalogs for design repositories

Workshops

Role of Empirical Studies in Understanding and Supporting Engineering Design

NIST co-sponsored a workshop entitled Role of Empirical Studies in Understanding and Supporting Engineering Design that was held at NIST in April 2002. The primary goal of the workshop was to bring academics and industry people together to create a better understanding of industrial design practice and the design of tools to support that practice. There were 23 participants from NIST, 5 European countries, and 4 universities and 3 companies.

Interagency Working Group for Engineering Design Meeting

Ram D. Sriram hosted a meeting for the Interagency Working Group for Engineering Design at NIST in July 2002. Participants from NASA, National Reconnaissance Office (NRO), Jet Propulsion Laboratory (JPL), National Science Foundation (NSF), TASC, and representatives from Triodyne, Lockheed Martin, and Boeing Company attended this meeting. The industry speakers presented their work and needs for design research. This was followed by a series of presentations from NIST staff and from participants from other agencies, including NSF, NRO, and JPL.

Program Standards Participation

American Society of Mechanical Engineers (ASME) Y14.5 Dimensioning and Tolerancing (GD&T)

Participate in committee activities.

American Society of Mechanical Engineers (ASME) Y14.5.1 Mathematical Definition of Dimensioning and Tolerancing Principles

Participate in committee activities.

ISO TC184/SC4/WG12 Industrial Data, Common Resources

Provide leadership for the Parametrics Group, which is developing Part 108 of STEP (Parameterization and constraints for explicit geometric product models) and a new approach to product shape modeling in terms of its constructional history.

OMG Manufacturing Domain Task Force (Mfg DTF)

Participate in OMG's Manufacturing Domain Task Force. This organization is responsible for setting the overarching strategy for the working groups that comprise the task force. Current activity involves participation in the development of CAD interface specifications.

ISO TC 184/SC4 Parametrics Project and Assembly Representation

Participate and provide leadership for ISO activities related to assembly and tolerance representation. SC4 is developing standards, which provide capabilities to describe and manage product data throughout the life of the product.

Shop Floor as a National Measurement Institute

Program Manager:
Steve Phillips

FTEs:	2.5
Program Funding:	$579 K

2003 Projects

- ASME B89.7.3.3 Guidelines for Assessing the Reliability of Dimensional Measurement Uncertainty Statements
- ISO 10360-2 Geometrical Product Specifications (GPS) for CMMs
- Laser Based Ball Bar and Ball Step Calibration
- Non-equilibrium Thermal Conditions
- Smart Artifact Round Robin

Program Goal

By FY2005, produce a suite of documentary standards, guidelines, and reports that will allow the U.S. industrial dimensional metrology community to support the assertion of measurement traceability to the Systems International (SI) unit of length, including the use of intrinsic standards.

Customer Needs

The globalization of the economy is strongly driving international standardization and accreditation programs, e.g., ISO 9000 and ISO 17025, as a means of assuring quality control of components fabricated throughout the world. Accrediting organizations such as American Association for Laboratory Accreditation (A2LA) experienced double digit annual growth for the past decade, particularly in the dimensional metrology field (classified under mechanical). Most of these standards and accreditation programs require traceable measurements and hence measurement uncertainty statements. Consequently, U.S. industry is under new pressures to comply with these requirements while being stymied by a poor understanding and incomplete development of measurement uncertainty and traceability issues. This program seeks to provide a set of documentary standards, guidelines, and reports to develop and elucidate this issue for dimensional metrology. Additionally, the program seeks to address specific problematic sources of uncertainty and conduct research to characterize these sources in a manner compliant with national and international standards.

Technical Approach

The Shop Floor as a National Metrology Institute (SF-NMI) program is a metaphor for enabling the dimensional metrology industry to consider issues normally associated with a NMIs, including connection to the SI unit; determining sources of uncertainty; quantifying sources of uncertainty; generating measurement uncertainty statements; and applying and validating uncertainty statements. The SF – NMI program has three principal thrust areas: (1) standards and document development for measurement uncertainty and traceability issues, (2) research and development (R&D) in specific technical areas involving measurement uncertainty, and (3) quality assurance activities such as industrial round robins and efforts to reduce the cost of metrology artifacts and calibrations. In all of these areas the program seeks a "faster, cheaper, simpler" approach consistent with industrial needs. The standards development thrust area seeks to provide a broad suite of standards, guidelines, and reports that form a coherent framework for the implementation of measurement uncertainty issues by U.S. industry. The program uses metrology experts from NIST, U.S. industry, Department of Defense, and academia to develop consensus documents that become widely available to U.S. industry. Emphasis is placed on developing a comprehensive and coherent approach to metrology that is both technologically available and economically reasonable. Significant consideration is given to anticipating the incorporation of these documents and concepts into future ISO standards.

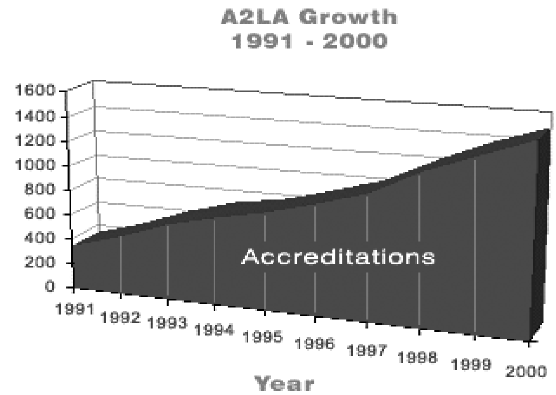
The standards development thrust focuses on the following areas:

- Measurement Uncertainty Evaluation and Reliability: Several issues hinder the generation or adoption of measurement uncertainty statements by the dimensional metrology community. The SF-NMI program is addressing topics such as a simplified approach to the Guide to the Expression of Uncertainty in Measurement (GUM) tailored to practitioners of dimensional metrology on the shop floor; advanced concepts in measurement uncertainty, including uncorrected bias and utilizing prior information; and methodologies to calculate measurement uncertainty, especially using computer simulation.
- Decision Rules: Many measurements are performed to determine if a product is in accordance with some specification, e.g., if a workpiece is within its specified tolerance. The measurement value is usually not retained; only the decision of whether the product is acceptable or not acceptable is recorded. This general class of problems is not addressed by the GUM and represents an important economic (and potentially conflict prone) application of measurement uncertainty. The SF-NMI program seeks to clarify this issue, provide unambiguous terminology, and establish a minimum set of conditions required for (as much as possible) a self consistent decision process through the use of guard-banding of the specification zone.
- Risk Analysis: The Role of Uncertainty in Conformance Testing: The calculation of an economically appropriate guard-band for a decision rule is a quantitative task that depends on an acceptable level of risk of accepting out-of-specification products or rejecting acceptable products. The SF-NMI program seeks to elucidate this issue and describe the factors that the industrial metrologist must consider when calculating guard-bands.

- Traceability and Calibration Concepts: The International Vocabulary of Basic and General Terms in Metrology (VIM) provides little insight as to when a measurement is traceable or when a measurement is considered a calibration (or not). These matters are frequently misinterpreted or in conflict (e.g., traceability does not necessarily indicate accuracy). Similarly, the question of whether or not a traceable measurement is required to have a direct lineage back to a NMI is often in debate. The SF-NMI program seeks to facilitate dimensional metrology by providing guidelines in these areas that represent the best thinking of the national and international metrology community.

The R&D objective addresses issues such as

- Non-Equilibrium Thermal Uncertainties in Workpieces and Coordinate Measuring Machines (CMMs): This project addresses the perennial (and typically intractable) problem of the impact of non-equilibrium thermal conditions. While rarely a problem in an NMI laboratory, it occurs (often at critical times) in industry. For example, when a manufacturing line is down due to components no longer assembling properly, a workpiece that is still hot from the manufacturing process is rushed to the 20 ° C CMM room for a rapid measurement. Presently, it is unknown to what extent the non-equilibrium conditions affect the workpiece geometry; this project seeks to develop rapid calculational methods to solve this problem. In 2002 a new work item was initiated to provide a general classification and consequences schema for various designs of CMMs and various thermal environments.
- Computer Simulation of Measurement Uncertainty Software: Monte Carlo calculational efforts are a powerful technique to evaluate measurement uncertainty. Most commercial software source code to not available for examination. This project seeks to explore methods for testing uncertainty evaluation software and provide recommendations to standards committees for best practices.



The rapid rise in laboratory accreditation programs over the last decade.

The quality assurance objective targets both reducing the cost of industrial dimensional metrology and validating the use of measurement uncertainty in the industrial environment. Specific projects include:

- The Smart Artifact: The smart artifact was adopted by the SF-NMI program in FY2002 as a continuation of an MEL exploratory project from FY2001. This project seeks to develop a calibrated artifact that serves as a surrogate workpiece containing advanced Geometric Dimensioning and Tolerancing (GD&T) features. The first goal is to generate a Measurement Assurance Program (MAP) for CMMs; MAPs are a required activity of most laboratory accreditation programs and are currently lacking for CMM activities. The second goal is to develop a MAP round robin that will allow, for the first time, an evaluation of industrial CMM measurement capability of real workpiece like features. The final goal is to turn over the smart artifacts to a proficiency testing organization where it will be integrated into their responsibilities for coordinating MAPs for U.S. industry.

- Complex Surface Fitting: This project addresses a special need of the CMM metrology community regarding complex surface fitting software. While many NMIs offer a software calibration service for elemental geometries, such as cylinders, spheres, or planes, no NMI offers this service for a complex surface. Although the development of a full calibration service for complex surfaces is beyond the scope of the SF-NMI program, we are developing several special case solutions. This will allow industrial metrologists involved with complex surfaces to have access to several test cases to test their complex surface fitting software evaluation.
- Laser Based Ball Bar Calibration System: This project is designed to address three issues: (1) The trend of international CMM standards is clearly toward the use of calibrated artifacts; while the U.S. ASME B89.4.1 standard on Coordinate Measuring Technology, does not yet have this requirement for its primary (ball bar) artifact; this system will meet this future need. (2) The laser-based metrology of the system represents a connection to the SI with minimal involvement from an NMI. (3) The system will reduce the cost of ball bar calibration by roughly 60 %, an important factor in encouraging the use of calibrated artifacts in industry. The system is now being considered for possible ball stepgauge calibrations.

Program Objectives and Technical Outputs

Objective 1:

By FY 2007, develop standards, guidelines and reports for traceability.

Technical Outputs

FY2003:
B89.7.3.3 "Guidelines for Assessing the Reliability of Dimensional Measurement Uncertainty Statements" published.

FY2003:
SF-NMI website contains supporting papers on traceability, measurement uncertainty and standards development.

FY2003:
Working draft of B89.7.3.2 "A Simplified Guide for Dimensional Measurement Uncertainty."

FY2003:
Working draft of B89.7.8 "Metrological Traceability of Dimensional Measurements to the SI Unit of Length."

FY2003:
Final draft of B89.7.4 "The Role of Measurement Uncertainty in Conformance Testing."

FY2004:
Final draft of B89.7.3.2 "A Simplified Guide for Dimensional Measurement Uncertainty."

FY2004:
B89 main committee and Board of Standardization approval for B89.7.4 "The Role of Measurement Uncertainty in Conformance Testing."

FY2004:
Final draft of B89.7.8 "Metrological Traceability of Dimensional Measurements to the SI Unit of Length."

FY2005:
B89 main committee and Board of Standardization approval for B89.7.8

"Metrological Traceability of Dimensional Measurements to the SI Unit of Length."

FY2005:
B89 main committee and Board of Standardization approval for B89.7.3.2 "A Simplified Guide for Dimensional Measurement Uncertainty."

FY2005:
B89.7.4 "The Role of Measurement Uncertainty in Conformance Testing" published.

FY2005:
Working draft of B89.7.7 "Advanced topics of Measurement Uncertainty and Extensions of the GUM."

FY2006:
B89.7.8 "Metrological Traceability of Dimensional Measurements to the SI Unit of Length" published.

FY2006:
B89.7.3.2 "A Simplified Guide for Dimensional Measurement Uncertainty" published.

FY2006:
B89 main committee and Board of Standardization approval for B89.7.7 "Advanced topics of Measurement Uncertainty and Extensions of the GUM."

FY2007:
B89.7.7 "Advanced topics of Measurement Uncertainty and Extensions of the GUM" published.

Objective 2:

By FY2003, perform R&D focusing on some specific aspects of measurement uncertainty for industrial dimensional metrology including non-equilibrium thermal conditions and simulation software testing

Technical Outputs

FY2003:
Non-equilibrium thermal conditions: Published document on non-equilibrium thermal conditions of workpieces as NIST Internal Report (NISTIR)

FY2003:
Non-equilibrium thermal conditions: Classification and thermal response schema for Coordinate Measuring Machines (CMMs).

FY2003:
Non-equilibrium thermal conditions: CMM thermal issues published as NIST Internal Report (NISTIR).

Objective 3:

By FY2004, perform quality assurance activities on complex surface fitting service, the smart artifact system, and laser-based ball calibration system

Technical Outputs

FY2003:
Complex surface fitting: Results of the best-fit least-squares solution calculated for each complex surface with each data set published on NIST web site

FY2004:
Smart Artifact: Calibrated artifacts with characterized uncertainties.

FY2003: Smart Artifact: At least six CMM measurement labs identified for round robin participation.

FY2005:
Smart Artifact: Round robin results published in the NIST Journal of Research.

FY2003:
Laser Based Ball Bar Calibration System: Laser Based Ball Bar Calibration System validated via intercomparison to the M48.

FY2004:
Laser Based Ball Bar Calibration System: Findings of laser-based ball bar calibration system published in Journal of the American Society for Precision Engineering (ASPE)

Anticipated Impacts

The results of the SF-NMI program will begin to affect the metrology community towards the end of 2003, at which time several ASME standards or guidelines will be published and the SF-NMI website will be completely revised to provide guidance documents to U.S. industry. The SF-NMI program anticipates

- more streamlined and consistent laboratory accreditations through the removal of inconsistencies and improved understanding of traceability and measurement uncertainty issues,
- projection of the U.S. metrology viewpoint into the ISO standards area, and
- injection into industrial dimensional metrology considerations the economic benefits of considering measurement uncertainty.

Accomplishments of the Past Year

Development of standards and documents for measurement uncertainty and traceability issues:
Published ASME B89.7.3.1 "Guidelines for Decision Rules: Considering Measurement Uncertainty in Determining Conformance to Specifications."

Obtained B89 main committee and Board of Standardization approval for B89.7.3.3 "Guidelines for Assessing the Reliability of Dimensional Measurement Uncertainty Statements."

Produced working draft of B89.7.4 "The Role of Measurement Uncertainty in Conformance Testing."

Published and presented at the 2002 International Dimensional Workshop: "Standards for Traceability and Uncertainty in Dimensional Measurements."

R&D of measurement uncertainty for industrial dimensional metrology included:
Examined nonsymmetric part geometries for non-equilibrium thermal model.

Initiated exploratory project for non-equilibrium thermal classification of CMMs.

Quality assurance activities included:
Mathematically defined several complex surfaces.

Produced data sets with error perturbations for complex surface fitting project.

Developed and validated best least squares solution to data sets for complex surface fitting project.

Three Smart artifact billets manufactured and heat treated.

Machined Smart artifacts Ni plated.

GD&T developed and verified for Smart Artifact.

Fully instrumented one smart artifact.

Received first completed version of Laser Based Ball Bar Calibration System; returned prototype to University of Florida.

Software for Laser Based ball bar measurements developed.

Standards Participation

- ASME B89 Consensus Committee on Dimensional Metrology –member.
- ASME B89.4 Coordinate metrology – chair.
- ASME B89.4.20 CMM Traceability – member.
- ASME B89.7 Dimensional Metrology, Measurement Uncertainty –member.
- ASME B89.7.3 Decision Rules – chair.
- ASME B89.7.4 General Principles for Measurement System – member.
- ASME B89.7.7 Advanced Uncertainty Concepts – member.
- ASME B89.7.8 Traceability of Dimensional Measurements – chair.
- ASME H213 Technical Advisory Group (TAG) Special Committee on Harmonization of Dimensional and Geometrical Product Specifications and Verifications – member.
- ISO TC 213 WG 10 Dimensional and geometrical product specifications and verification, Coordinate Measuring Machines - subject mater expert.
- ISO TC 213 WG 4 Dimensional and geometrical product specifications and verification, Uncertainty of measurement and decision rules - subject mater expert.

Program Manager: Johannes Soons

FTEs:	5
Program Funding:	$866 K

FY2003 Projects:

- Machine Tool Performance Characterization
- Predictive Tolerance Analysis of Machined Parts
- Management of Machine Tool Performance Data
- Model-Based Quality Control and Improvement
- Metrology Concepts for In-Situ Inspection
- Condition Monitoring of Machine Tool Spindles
- Smart Sensor Interfaces and Standards for Condition Monitoring

Smart Machine Tools

Program Goal

In collaboration with industry, develop, validate, and demonstrate the enabling metrology, smart sensor technology, and standards needed to characterize, monitor, and improve the accuracy and reliability of machining and turning centers, leading to the realization of autonomous smart machine tools that machine the first and every subsequent part to specification without unscheduled delays.

Customer Needs

Machine tools are used for discrete part and tooling fabrication, and hence are integral to the manufacture of durable goods. While the machine tool industry is relatively small, U.S. purchases and shipments in 1999 totaled $6.5 billion and $3.7 billion, respectively, it has a highly leveraged impact on almost every aspect of daily life. A study by the Association for Manufacturing Technology (AMT)[1] credits advancements in machine tools and related manufacturing technologies for benefits worth a total of nearly $1 trillion in the United States over the period 1994-1999. These benefits resulted from gains in productivity; declines in inventory requirements; and manufacturing-related product improvements for price, quality, and energy efficiency.

Machine tools for material removal (e.g., milling, turning, drilling, and grinding) are the most prevalent types of machine tools. Their users are faced with the challenge of intense global competition while moving to more complex parts, closer tolerances, smaller batch sizes, shorter time-to-market, just-in-time production, more general-purpose equipment, “green” manufacturing and global manufacturing. Success in this environment depends on the availability of accurate and reliable machines whose performance is known and “guaranteed” for a wide variety of tasks and operating conditions. The capability of an enterprise and its suppliers to meet these requirements largely determines the range and features of products that can be produced, the extent to which the first and every subsequent part meets specifications, and the efficiency and agility of operations.

This program addresses the metrology, standards, and smart sensor systems needed to characterize, monitor, and improve the accuracy and reliability of machine tools for material removal. The emphasis is on agile environments. Critical needs have been compiled from a variety of sources, such as the AMT’s 1996 “Technology Roadmap for the

Machine Tool Industry," the 1998 Integrated Manufacturing Technology Roadmap (IMTR)[2] for manufacturing processes and equipment, reports from the National Research Council (NRC), industry and other agency visits, comments from standards committees, and several workshops sponsored by NIST and other organizations. An example is the following quote from the AMT roadmap:

> "With increased attention being placed on the capability of manufacturing equipment to maintain processing consistency (repeatability), improved techniques are required to monitor, diagnose, and adjust for causes of inaccuracy. These compensation and diagnostic features are viewed as an integral part of meeting increased process capability requirements. ... In addition to monitoring the process, techniques are also required to monitor the health of the machine and ancillary equipment, and to provide for the early detection of component failures."

The following are the identified critical needs in the areas of machine tool accuracy and reliability to which this program will make a contribution:

- Improved methods for the performance characterization of machine tools with associated error models and harmonized standards. The standards are required to 1) specify the mutual obligations, deliverables, and methods of verification between users and vendors; 2) analyze machine capability, in particular regarding the expected tolerances of machined parts; 3) unambiguously compare the performance of machines; and 4) monitor, diagnose, and improve machine performance. Performance characterization is difficult because there are many geometric, dynamic, and thermal sources of errors that change over time and whose effects on part accuracy are complex. With the data difficult to obtain and apply, (regular) performance characterization is not a common practice. Key needs are 1) harmonization of both performance parameters and methods of verification; 2) the identification of a small number of performance parameters that are unambiguous, comprehensive, and have an intuitive relation to the capability of a machine to perform specific tasks under various conditions; 3) simplified and less intrusive acceptance and periodic tests; 4) improved characterization of machine performance under loaded conditions; 5) updated procedures addressing technology advances of machine tools and testing equipment; and 6) procedures to translate generic performance parameters into machined tolerances of specific parts, so as to facilitate the harmonization of machine capabilities with part design, the diagnosis of part errors, and the assurance of part quality in agile environments.

Application of a grid encoder to test and improve the contouring performance of a machining center

- Improved machine tool accuracy, including self-monitoring and self-optimizing capabilities. The AMT roadmap targets an 80 percent improvement in accuracy between 1995 and 2010.
- Machine-centric quality control. In an agile environment, traditional quality control based on trends in the dimensions of similar parts is often not an option. Instead, techniques are desired that directly address a key error source, the performance of the used machining equipment. Another need in this area is the capability to inspect or validate parts on the machine tool.

1 "Producing Prosperity - Manufacturing Technology's Unmeasured Role in Economic Expansion", 2000.

2 Now maintained by the Integrated Manufacturing Technology Initiative (IMTI), www.imti21.org

- Standardized electronic data formats for machine tool performance and definition data. This will enable efficient access to these data by manufacturing applications such as electronic commerce, accounting, maintenance, performance tracking, quality control, process planning, programming, and simulation. The current plethora of incompatible and incomplete formats for machine tool data resulted in 1) duplicate efforts by companies to build databases with data on their machine tools; 2) systems and applications that cannot efficiently exchange data; and 3) a lack of commercially available tools and applications to archive and analyze data (e.g., trend analyzes end virtual machining software to predict part tolerances).
- Improved reliability of machine tools, including capabilities to track equipment condition on a real-time basis, offer on-line (remote) problem diagnosis, and provide condition-based maintenance (CBM). The capability to sense potential problems prior to failure reduces unexpected downtime and prevents damage to part and machine. The AMT roadmap targets improvements in reliability, as expressed by the mean time between failures (MTBF), by a factor of four between 1995 and 2010.

Technical Approach

Program staff are working with industry, academia, and Other Agencies to develop the enabling metrology, smart sensor systems, and standards for a new generation of so-called smart machine tools with the intelligence to interpret and communicate their improved accuracy and reliability in part-specific terms. The focus is on enabling the following capabilities for computer numerically controlled (CNC) machining and turning centers:

- The smart machine tool will know its performance and can be interrogated on this (self-identification). Its respective database can be queried and updated through standard protocols. One application is to predict whether a part can be machined to requested tolerances.
- The smart machine tool will monitor and optimize itself. It monitors error sources and compensates (self-calibration, self-diagnosis, self-correction, and self-tuning). Additionally, it will have smart components that can sense impending failure, request maintenance, and can be diagnosed remotely.
- The smart machine tool will assess the quality of its work. It can estimate the realized part tolerances from data obtained during the process or in-situ part measurements.
- The smart machine tool will be able to learn. It uses data obtained during and after the machining process, such as inspection data from a measuring machine, to update its performance model.

Research from the program contributes to the performance characterization and improvement of contemporary machine tools. This is the research area with the largest near-term impact, with many collaborative projects focusing on specific industry needs while still contributing to the long-term goal. A key aspect of the program is the demonstration and validation of prototype smart machine concepts on two testbeds: an advanced five-axis milling machine at NIST, and a turning center at the U.S. Army Picatinny Arsenal. Annual demonstrations of increasing sophistication will be held throughout the duration of the program.

Smart machine tools need smart transducers. The various roadmaps identify intelligent sensing techniques as an important means of achieving reliable and improved manufacturing operations. The extensive and cost-effective application of smart transducers is, however, inhibited by the lack of standard interfaces for connecting transducers to microprocessors and field networks. In response to industry's need, the program provides leadership in the development of the Institute for Electronics and Electrical Engineers (IEEE) 1451 family of standards providing an open standardized method of tying transducers to network buses. With IEEE 1451, transducers will have the intelligence to identify themselves and work with any type of industrial bus and instrumentation system on the market, enabling "plug-and-play" integration. With the networking capability, transducer data can be easily passed through the local area network to the Internet, facilitating remote monitoring applications and enterprise connectivity. Wiring is simplified and more reliable while facilitating signal processing using embedded systems.

Program research is guided by strong interactions with standards committees, academia, and industry (including system integrators and users and manufacturers of machine tools, machine test equipment, manufacturing software, and transducers). The program interacts synergistically with other MEL programs in Predictive Process Engineering, Intelligent Open Architecture Control of Manufacturing Systems, and Shop Floor as a National Metrology Institute.

Program Objectives and Technical Outputs

Objective 1:

By FY2005, enhance measurement methods, models, and parameters for the performance characterization of milling and turning centers, with a focus on practical, intuitive, yet comprehensive performance parameters and associated validation tests. Address new developments in machine tools and test metrology. Provide leadership to facilitate the development of the respective national and international standards.

Technical Outputs

FY2003:
1) Draft International Standard ISO 230-7: "Axis of rotation"; 2) Recommendation to ISO on updates to ISO 230-3 "Thermal Effects of Machine Tools; 3) Report to ASME B5.54 on dynamic measurements of geometric errors; 4) Report to project sponsor detailing procedures and results of an extensive baseline performance evaluation of a testbed turning center; 5) Completed study on performance measures for high-speed contouring and procedures to facilitate tuning of controller parameters.

FY2004:
Validated (virtual machining) procedures to translate generic performance data available in industrial environments into expected tolerances of parts, providing graded tradeoffs between uncertainties of the predictions and the required detail in analysis and data.

FY2005:
1) Harmonized and unbiased U.S. and ISO standards on machine tool performance evaluation that incorporate the latest science in machine tool technology and test methods; 2) Restructured U.S. standards into smaller generic and machine-specific sections; 3) Representation of U.S. interests in ISO by providing the Secretariat of ISO/TC39/SC2 "Machine Tool Test Conditions."

Objective 2:

By FY2003, develop unambiguous standardized eXtensible Markup Language (XML) data formats for machine tool performance data. Provide facilities to demonstrate, promote, and test conformance of the emerging standards and technology for interoperability. Develop machine tool self-identification capability enabled by an internal database of performance data that can be queried and updated through standard protocols.

Technical Outputs

FY2003:
1) Mature drafts, reference XML-schemas, and comprehensive collection of XML examples for ASME B5.59-1 "Data specification for machine tool performance tests," and B5.59-2 "Data Specification for the Properties of Machining and Turning Centers", 2) Smart machine tool database with web interface providing self-knowledge of turning center testbed as defined by data elements in B5.59-1 and B5.59-2.

Objective 3:

By FY2004, develop standards for smart sensor interfaces, wireless sensor connectivity, and sensor network capability relevant to manufacturing. Provide facilities to demonstrate, promote, test conformance, and validate emerging standards and technology for interoperability. Apply generic, standardized, smart transducer connectivity infrastructure to machine tools, with real-time processing of sensor data by embedded systems.

Technical Outputs

FY2003:

1) Establishment of an open source collaborative framework that allows industry, government, and academia to participate in the development of an unified implementation of IEEE 1451.1; 2) An open source-based IEEE 1451 embedded NCAP that demonstrates a distributed measurement and control system for Machine Tool monitoring and control; and 3) A balloted IEEE Standard for a Smart Transducer Interface for Sensors and Actuators-Mixed Mode Communication Protocols and Transducer Electronic Data Sheet (TEDS) Formats, IEEE Standard P1451.4.

FY2004:

Ballot-ready IEEE 1451.5 wireless smart transducer interface specification.

Objective 4:

By FY2005, develop smart sensor systems and procedures to monitor and adjust machine parameters that affect form and size of parts manufactured on the smart machine tool test bed, including use of process-intermittent and post-process inspection data and techniques for in-situ inspection.

Technical Outputs

FY2003:

Procedures, validated on testbed, to monitor machine tool error sources from post-process and process-intermittent inspection data.

FY2004:

1) Exploratory report on metrology concepts enabling machine tools to self-assess errors and provide in-situ inspection of machined parts; 2) Implementation and evaluation of various error reduction techniques on testbed.

Objective 5:

By FY2005, identify main failure modes of key machine components and develop procedures and sensor applications to detect and (remotely) diagnose abnormal machine behavior, and heightened probability of failure.

Technical Outputs

FY2003:

Report on the robust application of sensors and signal processing techniques to monitor the condition of machine tool spindles, emphasizing a physics-based understanding.

FY2004:

Report on methods and potential standards for specifying and estimating the MTBF of machine tools.

Anticipated Impacts

Anticipated impacts of the program include 1) improvements in productivity, time-to-market, and quality through smart machine tool concepts that facilitate the harmonization of part design with machine capability, machining the first and every subsequent part to specification, and machine maintenance; (2) harmonized machine tool performance standards that better address realistic production capabilities; (3) efficient exchange and application of machine tool data through standardized unambiguous data formats; (4) simplified and reliable transducer application in products and manufacturing through the network and enterprise connectivity and "plug-and-play" integration provided by IEEE 1451, leading to cost-effective integration of embedded intelligence and sensor technology; and (5) new market opportunities through standards and new product capabilities for manufacturers of machine tools, machine tool test equipment, manufacturing software, and transducer systems.

Accomplishments of the Past Year

Machine Tool Performance Standards

Provided Secretariat functions for ISO and ASME. Prepared and edited drafts, organized and hosted meetings, and maintained 60 international standards. At a recent meeting, industry participants expressed their deep appreciation for NIST's work on performance standards. Accomplishments include: 1) the revised ASME B5.54 Standard on the performance evaluation of machining centers, 2) recommendations for restructuring U.S. machine tool performance standards, 3) draft revision of ISO 230-3 "Determination of Thermal Effects", 4) Working Draft for ISO 230-7 "Axis of Rotation", accepted to proceed to DIS, and 5) comments on international proposals for uncertainty parameters

Linear Motor Testbed

Upgraded testbed to study the behavior of different types of machine scales under high accelerations. Completed screening experiments on the effects of controller parameters on dynamic stiffness, damping, positioning repeatability, and heat generation. Studied failure modes and possible measurands to indicate zones with heightened probability of impending failure.

Mean Time Between Failures Estimation

Conducted exploratory study with Southern University on the possible application of existing methods to analyze the reliability of complex systems from sub-component information to specify the mean time between failure of machine tools.

Contouring Performance

Prepared draft report on initial results of our research with the University of Korea on performance parameters and tests yielding a comprehensive picture of a machine's contouring capability, in particular for high-speed machining. Started research on tests and associated analysis procedures to facilitate automated tuning of controller parameters.

Power Quality Standards for Machine Tools

Submitted journal paper summarizing research with the Electric Power Research Institute (EPRI) on reduction of costly interruptions and performance degradation of machine tools due to power quality events in factory environments. Became charter member of task force established to study the need for power quality standards.

Study on Surface Location Errors

Collaborated with the Predictive Process Engineering program, Washington University, and the University of Florida on the measurement and prediction of surface location errors in high-speed machining and submitted a paper on the results.

Draft Standards for Machine Tool Performance Data

Provided major updates to the draft standard ASME B5.59-1 "Data Specification of Machine Tool Performance Tests," addressing comments from industry while completing the family of test classes that need to be addressed. Provided first draft of ASME B5.59-2 "Data Specification for Properties of Machining and Turning Centers" and generated associated XML schema.

Distributed Database for Machine Tool Performance Data

Developed prototype web-based application for exchanging machine tool properties and performance data in XML from distributed databases, each representing a simulated smart machine tool with self-knowledge and self-identification capabilities.

IEEE 1451 Open Source Repository Framework

Developed framework proposal, licensing structure, and technical approach required to register an IEEE 1451-based Open Source repository with the SourceForge site. Collaborators include several large manufacturing-related companies such as Agilent and Boeing.

Application of IEEE 1451 for Machine Tool Condition Monitoring

Developed an IEEE 1451 Web-based hardware and software framework for monitoring a machine tool. Java-based real-time video was integrated to provide visual feedback to the remote operator.

Application of IEEE 1451 to Condition Monitoring on Navy vessels

The NIST IEEE 1451.1 software reference implementation was completed and distributed via CD-ROM to CRADA partner AEPTEC. The CD-ROM contains the implementation, applications, and documentation. AEPTEC has been using a subset of the NIST developed implementation in some of their US Navy Ship trials.

Integration of Standards for Sensor Data

Published and presented a paper titled, "Sensor Network and Information Interoperability – Integrating IEEE 1451 with MIMOSA and OSA-CBM", at the Instrumentation and Measurement Technical Conference. The paper identifies the application entry points that allow OSA-CBM and IEEE 1451 to co-exist within the MIMOSA framework.

Collaboration on Model-Based Control

Started project with U.S. Army Picatinny Arsenal and industry partners on Model-Based Controller approaches to improve turning operations at the Arsenal and its suppliers. We are tasked with the development and documentation of procedures to improve part accuracy through automated model-based error compensation techniques fully integrated in the controller, including: pre-process "calibration" and periodic verification, process-intermittent feedback, and post-process feedback

Model-Based Quality Control

Developed a new concept for a systematic approach to improve over time the fidelity of a machine tool error model using the diverse and often incomplete data typically encountered in industrial environments. Data examples include inspection results of machined parts and results of quick periodic tests.

Signal analysis for condition monitoring

Completed instrumented testbed to analyze and improve sensor applications and associated signal processing techniques to monitor the condition of machine tool spindles. Prepared collection of spindle bearings with seeded defects for analysis. In collaboration with NASA, studied the novel Hilbert-Huang approach to signal analysis which holds a promise to address the nonlinear and non-stationary nature of accelerometer signals generated during machining. Wrote a report.

Workshops

Smart Machine Tools workshop

Collaborated with the Integrated Manufacturing Technology Initiative (IMTI) and NSF on a smart machine tool workshop to be held in December 2002. The workshop and the Smart Machine Tools program were highlighted in the September issue of Mechanical Engineering Magazine.

Smart Sensor Workshops

Organized and conducted several workshops and demonstrations with organizations such as IEEE, Sensors Magazine, and Sensor Expo and Conference: 1) workshop on Built-in-Test (BIT) Technology for smart sensors and systems, 2) workshops on requirements for new wireless sensor interface standards, resulting in the establishment of an IEEE study group on a common interface standard for wireless sensors, 3) workshops on enhancing and extending the IEEE 1451.2 Smart Transducer Interface Standard, 4) two technical sessions and collaborative demonstrations on smart sensors at the National Manufacturing Week conference and exposition, 5) Invited talk "IEEE 1451 Smart Transducer Standards" at the NSF workshop "Tether-free technologies in e-Manufacturing, e-Maintenance, and e-Service" and at the DoE workshop on Instrumentation, Controls, and Human-Machine Interfaces.

Standards Participation

ANSI/ASME B5 "Machine Tools - Components, Elements, Performance, and Equipment"

Member; Member B5/TC52 "Performance Evaluation of Machine Tools," editor ASME B5.54 "Performance Evaluation of Machining Centers"; Chair B5/TC56 "Information Technology for Machine Tools," editor B5.59-1 "Data Specification for Machine Tool Performance Tests" and B5.59-2 "Data Specification for Properties of Machining and Turning Centers."

ANSI/ASME B89.3.4 Axis of Rotation

Participating in the revision of the standard and liaison to ISO TC39.

ISO TC39 "Machine Tools"

Member; Secretariat TC39 SC2 "Test Conditions for Machine Tools," covering approximately 60 standards including the ISO 230 series "Test Code for Machine Tools"; Member WG1 and editor of ISO 230-1 "Geometric accuracy of machines operating under no-load or finishing conditions"; Member WG3 "Test Conditions for Machining Centers; Convener WG6 and editor ISO 230-3 "Thermal Effects of Machine Tools," and Editor ISO 230-7 "Axis of Rotation."

IEEE I&M Society, TC9 Sensor Technology

Chair; liaison of the I&M Society to the IEEE Standards Committee; coordinator and member of IEEE P1451.3 "Digital Communication and Transducer Electronic Data Sheet (TEDS) formats for Distributed Multidrop Systems," IEEE P1451.4: "Mixed-mode Communication Protocols and TEDS formats," IEEE P1451.5: "Wireless Smart Transducer Interface Specification," and IEEE P1588: "Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems."

Program Manager
Theodore Vorburger

FTEs:	8.5
Program Funding:	$887 K

FY2003 Projects

- C-AFM Development
- Standards for Bullets and Casings
- Pitch/height Standard Reference Materials
- Surface Calibration Database
- Surface Metrology Impact
- SEM Magnification Standards
- Line Edge Roughness Measurement

SURFACE METROLOGY

Program Goal

By 2005, deliver with world leading levels of uncertainty to the U.S. metalworking and semiconductor industries and to the law enforcement community the most critical measurement service or standard required by each in the field of surface and micrometrology. Use of these services and standards will lead the development of new markets, new products, and new information systems in these sectors.

Customer Needs

Metal and electronic products constitute a large portion of U.S. economic output. According to the “U.S. Industry and Trade Outlook 2000[1],” the value of shipments by U.S. manufacturers in motor vehicles alone was forecast to be $225 billion in 2000. For the microelectronics and aerospace industries, those figures were forecast to be $189 billion and $136 billion, respectively. The functional properties of metal and electronic products that are affected by the surface finish include friction and wear, semiconductor integrity, and optical imaging quality. Therefore, many functional surfaces of these products must be specified and measured for surface finish as well as for the dimensions of certain microscopic surface features. The accuracy and relevance of industrial measurements depend on NIST calibrations and research to provide traceable measurements of a wide range of roughness parameters using modern digital filter techniques.

Technical Approach

The Surface Metrology program provides calibrations and services that support surface metrology and scanned probe microscopy (SPM); applies the calculation of electromagnetic wave scattering to critical surface metrology problems; supports industry’s efforts to develop national and international documentary standards in surface metrology and SPM; provides standard reference materials (SRMs) that industry cannot supply for itself; and resolves divergences in surface measurements between different techniques, different laboratories, and different countries.

[1] http://www.ita.doc.gov/td/industry/otea/outlook/

We primarily use high-resolution profiling instruments to perform calibrations of standards and tests of industrial components. These instruments include five stylus instruments, the calibrated atomic force microscope (C-AFM) and two other atomic force microscopes (AFMs), and two optical interferometric microscopes. In addition, we developed the world's first metrology scanning electron microscope (SEM), which provided calibrations of approximately 750 SEM calibration standards over 17 years. The profiling instruments are calibrated directly with laser interferometers or indirectly with master artifacts calibrated by optical interferometry. Using new techniques we are continuously upgrading either the hardware or software of these instruments or the calibration of our master artifacts; improving the accuracy, automation, and flexibility of our instruments to meet new customer requirements; or producing new SRMs. Most of the SRMs produced by MEL come from this program.

Feedback from our collaborators (i.e., semiconductor manufacturers, instrument vendors, and vendors of specimen standards) play an important role in determining our technical priorities. We participate in industrial round robin intercomparisons, like that for the single atom step height specimens, as one potential means of developing a calibration standard. Roadmaps, such as the International Technology Roadmap for Semiconductors (ITRS) and Optoelectronics Industry Development Association (OIDA), influence the directions we take and the ambitious goals that we set. We also collaborate closely with other National Measurement Institutes (NMIs) and foreign laboratories.

During FY2003 we are completing work on CIPM-coordinated key comparison and a SIM (Interamerican Metrology System) coordinated regional comparison. We will develop a procedure for use of single atom step height standards and make available new bullet standards. We will facilitate the publication of the 2002 revision of the American Society of Mechanical Engineers (ASME) National Standard B46.1-1995, "Surface Texture."

Program Objectives and Technical Outputs

Objective 1:

By FY2003, complete development of a C-AFM based laboratory capability to measure pitch with improved range and uncertainty to support US metrology suppliers to the semiconductor and other nanotechnology industries.

Technical Output

FY2003:
System characterization, measurements, analysis, and report for an external customer completed for pitch measurement with the C-AFM, with uncertainty budget showing at least a factor of two improvement over previous uncertainty budgets for the C-AFM.

Objective 2:

By FY2004, complete measurements, calculations, and documentation for NIST Reference Materials for both standard bullets and casings, thus supporting the National Integrated Ballistics Information Network with required physical standards.

Technical Outputs

FY2003:
Thirty RM (Reference Materials) 8240 Standard Bullets fabricated by numerically controlled diamond turning, then measured, analyzed, and released for distribution.

FY2004:
RM 8250 Standard Casings received, measured, analyzed, certified, and released for distribution.

Objective 3:

By FY2006, complete the certification of SRM 2089 having calibrated pitch features in the x- direction and calibrated step heights in the z-direction for calibration of SPM used in nanotechnology industries.

Technical Outputs

FY2003:
Purchase order issued with accompanying specification for pitch/height specimens with approximately 50 nm step height and submicrometer pitch.

FY2004:
Report of measurements completed for acquired pitch/height specimens indicating their suitability as SRM2089.

FY2005:
Measurements and initial analysis for the SRM pitch/height specimens.

FY2006:
SRM 2089 Specimens analyzed, certified, and delivered for distribution.

Objective 4:

By FY2005, develop a Web-based information system for verification of industrial software for surface texture analysis in support of the automotive and aerospace industries.

Technical Outputs

FY2003:
Surface profile data and associated calculated parameters made available on a public NIST website for two-dimensional (2D) surface profile examples used in the ASME software round robin of 1998.

FY2004:
Three-dimensional (3D) surface topographic data and associated calculated parameters made available on a public NIST website.

FY2005:
Website communications and software developed to enable NIST analysis of submitted user surface data.

Objective 5:

By FY2005, complete a canvassing of U.S. industry for assessment of impacts of the NIST Surface Metrology Program.

Technical Outputs

FY2003:
Plan for a canvassing of industrial users to assess the impact of the NIST Surface Metrology Program.

FY2005:
Report issued on the Impact Study for the NIST Surface Metrology Program.

Objective 6:

By FY2006, complete the measurement and certification of SRM 2070, SEM Magnification Standard, and release for distribution to industrial users of SEMs.

Technical Outputs

FY2003:
Measurements completed of SRM 484 and 2070 masters with Amray SEM; uncertainty budget developed for production measurements of SRM 2070 samples with the Amray.

FY2004:
Measurements completed of SRM 484 and 2070 masters with C-AFM; uncertainty budget developed for production measurements of SRM 2070 samples with the C-AFM; decision made on choice of measurement tool for SRM 2070.

FY2005:
Measurements completed of SRM 2070 and results turned over to the Statistical Engineering Division for analysis.

FY2006:
Analysis and certification completed of SRM 2070; 100 units of SRM 2070 released to the SRM Group for distribution.

Objective 7:

By FY2007, complete development of a prototype measurement standard for line edge roughness, suitable for use by SPMs to address issues raised in the most recent ITRS.

Technical Outputs

FY2003:
Review article published on SPM-based techniques for measurement of line edge roughness (LER).

FY2004:
Design and acquisition plan for LER specimens developed in cooperation with IBM and other collaborators.

FY2006:
Samples measured and article published on NIST capability to measure LER with SPM.

FY2006:
Receipt of prototype LER specimens by NIST and by collaborators.

FY2007:
Joint article on measurement of prototype LER standards by NIST and industrial collaborators submitted for publication.

Anticipated Impacts

A successful program will enable the harmonization of U.S. industry surface metrology practices with international standards achieved to the extent that it enables the opening of significant ($0.3 B level) new foreign markets for U.S. metal worked goods; the development of semiconductors with critical dimension of 100 nm and smaller with NIST supplied traceable LER metrology; and the development of a National Integrated Ballistics Information Network relying on NIST-developed artifacts as physical standards.

Our development of a microform calibration system for Rockwell diamond indenters resulted in the lowest uncertainty in the world. As a result, one of the indenters we calibrated is now the NIST's primary standard indenter for calibration of SRM Rockwell C hardness blocks. A second indenter is used as a common indenter for a CIPM (International Committee of Weights and Measures) Key Comparison and was used in an earlier international comparison in hardness.

Accomplishments of the Past Year

C-AFM Development

Completed measurements, analysis, and reports for the CIPM's Nanometrology Preliminary Key Comparison in step height measurements. We produced reports for both stylus and C-AFM measurement techniques of five step heights ranging from 7 nm to 700 nm. The results for the two techniques agreed with each other to within their combined standard uncertainty. Draft A of the final results from all participants was made available to the participants on a confidential basis. This work will enable world-wide recognition of NIST step height calibration services under the international Mutual Recognition Arrangement (MRA).

Standard Bullets and Casings

Fabricated 20 standard bullets by numerically controlled diamond turning and distributed to partners at the Bureau of Alcohol, Tobacco, and Firearms (ATF) and Forensic Technology Incorporated (FTI) for initial measurements. These bullets are crucial to the development of a National Integrated Ballistics Information Network, a project led by the ATF.

Pitch-Height Standard Reference Materials

Redesigned the pitch-height specimens for improved manufacturability and user automation requirements.

Line Edge Roughness Measurements

Collaborated with IBM Almaden to organize an industry discussion group meeting on LER; Cooperated with ISMT in the specification of LER prototype standards;

Drafted review article of AFM measurement of LER in cooperation with IBM Almaden and University of North Carolina Charlotte.

Additional Research Accomplishments

C-AFM pitch measurements, performed earlier for VLSI Standards, Inc. with the C-AFM, used as the basis of a traceable SEM calibration standard with 100 nm pitch produced by VLSI Standards.

Completed editing of new revision of the ASME B46.1 national standard, "Surface Texture," in cooperation with industrial partner.

Co-authored draft report on the international comparison of surface roughness and step height standards SIM 4.8, intended for publication in Metrologia. We obtained excellent agreement with the reference values for the parameters Ra, step height, Rz, and RSm.

Three stages in the manufacture of standard bullets: From left to right, fired master, numerically controlled (NC) machined brass prototype, and NC machined Reference Material 8240.

Completed publication of the final results of a comprehensive industrial comparison of profile measurements of Si wafers. This study included measurements of twelve wafers ranging in rms roughness from 0.1 nm to 1 mm with six different techniques by NIST and four industrial partners.

In cooperation with two other NIST Operating Units, completed the Director's Competence Project on Coatings Appearance with publication in the Journal of Coatings Technology of an article on light scattering from metallic coatings

Completed participation with the NIST Materials Science and Engineering Laboratory on successful research to simulate the performance of Rockwell hardness indenters using finite element analysis with publication in the Journal of Testing and Evaluation

Achieved rapid progress and high industrial visibility in work to develop the ISMT's AFM-based Reference Measurement System for measurement of semiconductor critical dimensions through the assignment of a NIST employee as a Guest Researcher there.

Approximately 20 articles were published during the past fiscal year, including four in peer reviewed journals and a tutorial on measurement of surface roughness in the trade publication, Optical Engineering.

Standards Participation

ASME B46 National Standards Committee on the Classification and Designation of Surface Qualities

Member, former Chair of the Committee, and Chair of the Editorial Working Group that produced the 1995 revision of ASME B46.1, "Surface Texture," which has sold 4200 copies and the 2002 revision is in press.

ASTM E42.14 on Surface Analysis

Participant. Plan submission of procedure for z-calibration of AFMs at the atomic level.

ISO Technical Committee (TC) 164 on Sub-committee (SC) 3 on Hardness Testing

We are working with this group on the development of an international round robin for hardness measurement using indenters developed by NIST.

ISO TC213 Task Force on Three Dimensional Surface Texture

Appointed Chair of Project Team on Procedures for Optical Measurements of 3D Surface Texture

Measurement Services

Calibrations

15010C Roughness Calibration Specimens

Provide traceable measurements of the roughness average Ra and other roughness parameters for ISO and American National Standards Institute (ANSI) Type C roughness calibration specimens primarily for the mechanical parts industries.

15030C Step Height Measurements

Provide traceable calibrations of ISO and ANSI Type A step height standards used for calibration of surface topography instruments for the mechanical parts, microelectronics, and optics industries

15040S Special Surface Topography Tests

Provide traceable measurements of a range of roughness and surface topography parameters including the dimensional and geometrical properties of hardness indenters.

SRMs

SEM Magnification Standard
SRM 484 and SRM 2070

This popular standard, which has been restocked and sold out seven times (about 1000 specimens total), serves as the dissemination of the unit of length for SEMs, principally in the microelectronics and related industries.

Sinusoidal Roughness Blocks, SRMs 2071b, 2072, 2073b, 2074, 2075

This series of precision roughness standards provides certified values for both roughness height and spatial wavelength and is a component of MEL's dissemination of the unit of length primarily to the mechanical parts industries. Approximately 350 specimens have been sold altogether. SRM 2072 sold out. SRMs 2071 and 2073 sold out and have been recertified and restocked.

Program Manager
James Fowler

FTEs: 2.9
(program management)

Program Funding: $11,752 K

FY2003 Programs (MEL)

- Intelligent Open Architecture Control of Manufacturing Systems
- Manufacturing Enterprise Integration
- Manufacturing Simulation & Visualization
- Predictive Process Engineering
- Product Engineering

FY2003 Projects (Non-MEL)

- Data Uniformity and Standards in Structural Bioinfomatics
- Electronic Commerce for the Electronics Industry
- Information Technology (IT) Infrastructure Conformance Testing
- Interoperability of Databases for the Structure, Stability and Properties of Inorganic Materials
- Interoperability Standards for Capital Facilities

SYSTEMS INTEGRATION FOR MANUFACTURING APPLICATIONS (SIMA)

Program Goal

Reduce time-to-market for highly engineered products by improving the productivity of engineering and manufacturing through the widespread adoption of information standards.

Customer Needs

The need to share computer-interpretable information among different software systems—that is, the need for interoperability—is nearly as old as computing technology itself. Software interoperability generally is achieved by the use of decades-old techniques. Developers and/or users of software identify desired functionality across software boundaries, then specify the data to be shared across those boundaries to achieve that functionality, and finally create software on both sides of the boundary to communicate and interpret the specified data.

When software systems lack an inherent capability to share information, problems ensue. These problems are typically manifested as data transfer errors and the extra staff time required to manually fix or reenter data from one system into another. The costs resulting from such interoperability problems are high; annual costs of $1 billion were documented in analysis of interoperability costs in the U.S. automotive sector alone. [1] A lack of desired interoperability between software systems can be found in every industrial sector, in every software market, among different versions of the same software, among identical versions of the same software on different platforms, and among the identical versions of the same software on the same platform (reflecting different usage practices).

For decades, NIST has partnered with industry to address a variety of software interoperability problems. NIST's efforts in the solution of software interoperability issues are typically manifested as contributions to the technical content of voluntary standards through participation in standards developing organizations, development of reference software implementations of voluntary standards, and development of procedures for testing software that implements voluntary standards.

[1] http://www.mel.nist.gov/msid/sima/interop_costs.pdf

Such efforts have led to the adoption of software interoperability solutions such as the Structured Query Language (SQL), the Initial Graphics Exchange Specification (IGES), and the Standard for the Exchange of Product model data (STEP). These and similar NIST efforts are increasing the interoperability of software systems and resulting in concomitant higher labor productivity.

Still, increasing numbers of software interoperability solutions are being sought for a multitude of industries. Multiple factors are contributing to this growing need. Among them are:

- **Outsourcing of Business Functions**
  New requirements for software interoperability emerge when engineering or manufacturing activities that were formerly integrated internally are outsourced. The electronics industry is rife with examples of brand-name establishments outsourcing their manufacturing operations to contract manufacturing services, yielding new software interoperability requirements for both partners. Similarly, the automotive industry is increasing the engineering and manufacturing responsibilities of "super-suppliers" in the automotive supply chain and thereby heightening the needs for software interoperability between the automakers and their suppliers.
- **Mergers & Acquisitions/Joint Ventures**
  Software interoperability issues come to the forefront when companies acquire one another (e.g., Ford's acquisition of Volvo and Land Rover) or partner to pursue business opportunities (e.g., the Lockheed Martin, Northrup Grumman, and BAE Systems partnership for the Joint Strike Fighter program).
- **Increasing IT Deployment**
  The combined trends of diminishing hardware costs, increasing hardware performance, multiplying tiers of software offerings, ubiquitous network connectivity, and increasing broadband availability promulgate deployment of IT throughout the smallest business establishments and the most hide-bound industrial giants alike. Hence, formerly insular departments or companies find themselves connected to the world, seek to communicate in ways that were previously unthinkable, and then create the need for new interoperability solutions.
- **Increasing IT Capabilities**
  Each technical innovation in IT yields a plethora of software offerings intended to make software development exploiting that technical innovation easier and to provide end users with new software products leveraging that technical innovation. The continuous growth in software offerings and their associated functionalities creates unceasing need for new software interoperability solutions.

FY2003 Projects (Non-MEL) cont.

- Numerical Data Markup Language
- Online Access to NIST Chemical Reference Data
- Product Data Standards for Heating, Ventilation, and Air Conditioning/Refrigeration (HVAC/R) Systems
- Standards for Exchange of Instrument Data and NIST Chemical Reference Data - SpectroML
- Visualization and Virtual Reality for Collaboration and Manufacturing

Technical Approach

The SIMA Program supports technical efforts throughout all of NIST's seven laboratory organizational units and also collaborates with many other organizations.[1] These efforts contribute to the definition and creation of standards facilitating the exchange of manufacturing data within and across all levels of the product realization process. Objectives include the establishment of rigorous methods for defining and testing interoperability solutions; standards specifying information to be exchanged, as well as the interface mechanisms necessary to do so; and tests validating potential standards solutions and implementations.

There are four principal reasons why industries seek NIST's involvement in solution of interoperability problems:

- neutrality – NIST has no vested interest in the interoperability solutions being promulgated;
- rigor, integrity, and expertise – NIST has extensive domain knowledge combined with an established track record of contributions to interoperability solutions;
- breadth – NIST provides a multi-industry perspective; and
- permanence – NIST has a long-term perspective that is not subject to the whims of short-term market dynamics.

Program Objectives

For further information about SIMA-supported MEL programs, please look for the program description elsewhere in this publication.

Objectives for the SIMA Program Office:

Objective 1:
By FY2003, complete report describing the current status of the SIMA program and accomplishments of the constituent efforts over the previous two years.

Objective 2:
Provide evidence indicating current challenges faced by industry with respect to manufacturing software interoperability, current and forecasted market sizes, and publicly recognized NIST contributions to interoperability solutions.

Objective 3:
Manage funding for projects in other NIST laboratories such that those projects focus on solutions to interoperability problems faced by their respective industry customers.

Objectives for selected SIMA-supported non-MEL projects:

Objective 4:
Electronic Commerce for the Electronics Industry (ECEI): By FY2003, continue development of testbed for evaluating web infrastructure technology and services supporting Business-to-Business (B2B) e-business and e-manufacturing processes.

Objective 5:
IT Infrastructure for Conformance Testing: By FY2003, produce a conformance test suite framework for ebXML Messaging Services v2.0.

Objective 6:
Interoperability of Databases for the Structure, Stability and Properties of Inorganic Materials: By FY2003, produce MatML/XML representation for the Inorganic Crystal Structure Database, Ceramics Phase Diagram Database (PDFC), and Ceramics.

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[1] The many external organizations that participate in SIMA Program research are listed at http://www.mel.nist.gov/div826/msid/sima/collabs.htm

Objective 7:
Interoperability Standards for Capital Facilities: By FY2003, complete the International Standard version of ISO 10303 AP227 (Plant Spatial Configuration) second edition.

Anticipated Impacts

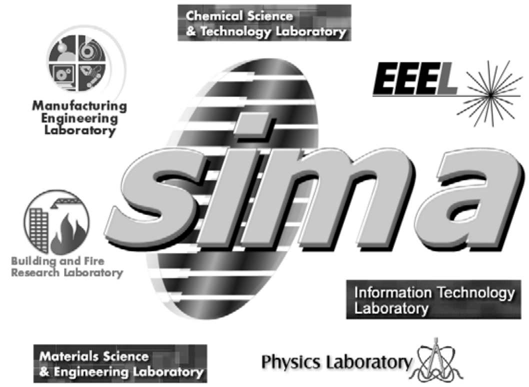
Anticipated impacts of the SIMA Program include shorter time-to-market for highly engineered products, lower operational costs for highly engineered products, seamless interoperability among software systems used in engineering and manufacturing, and improved access to NIST scientific and engineering data supporting research and development of new products in a variety of industries.

Accomplishments of the Past Year

Completed prospective strategic study analyzing economic costs of inadequate software testing. (Available at http://www.mel.nist.gov/msid/sima/sw_testing_rpt.pdf)
Completed retrospective economic study analyzing the economic benefits of NIST's efforts towards developing and deploying STEP.
http://www.mel.nist.gov/msid/sima/step_economic_impact.pdf

Other Information

The extensive set of external organizations that collaborate with SIMA research efforts is listed at http://www.mel.nist.gov/div826/msid/sima/collabs.htm.

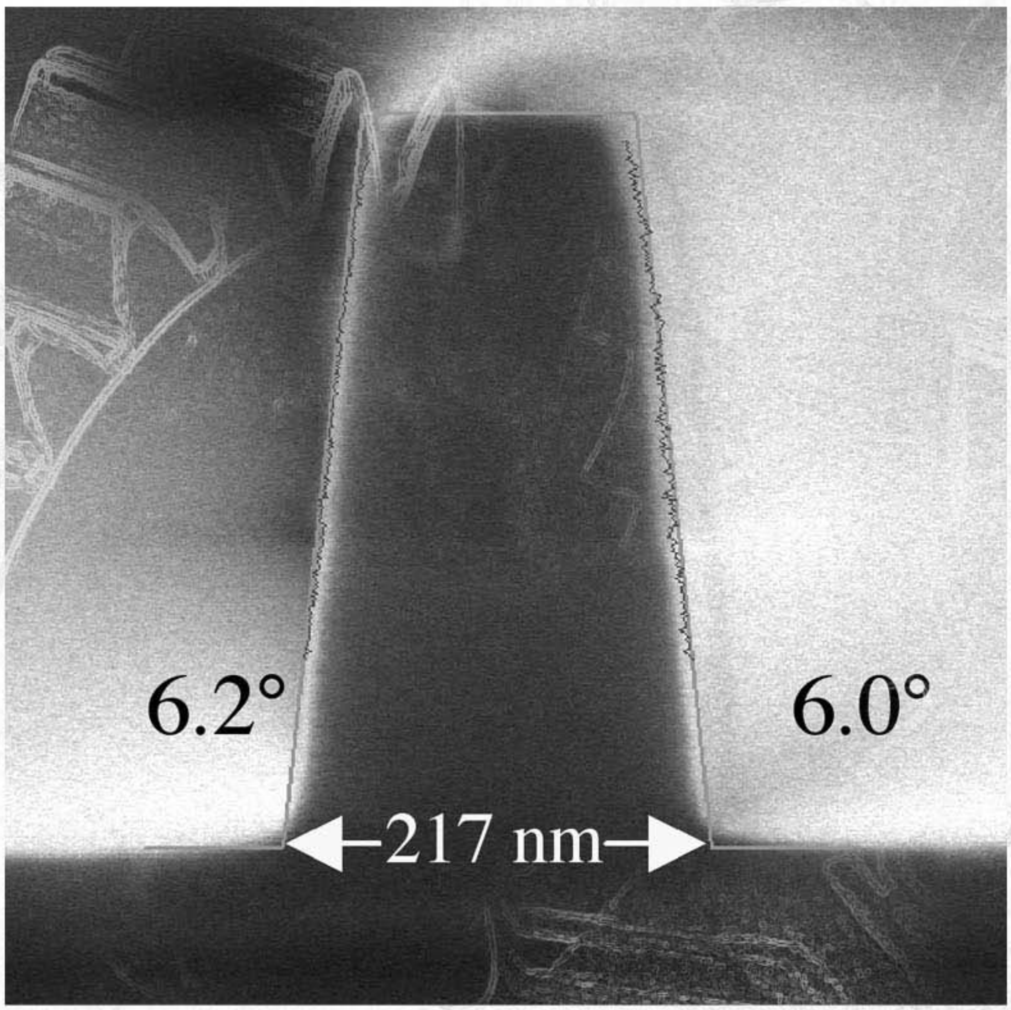


SIMA supports research in each of NIST's laboratories

Standards Participation

Researchers in SIMA-supported projects are involved directly in the development of at least 38 formal interoperability standards. This work is conducted through more than 50 organizations, including national and international formal standards organizations as well as various consortia and trade associations.

Special Programs and Projects



Special Programs and Projects

NIST is committed to working with partners in the international community to improve manufacturing operations, enhance international competitiveness and technology breakthroughs through a program called the Intelligent Manufacturing Systems (IMS) Program. IMS participants from Australia, Canada, the European Union and Norway, Japan, Korea, Switzerland, and the U.S. cooperate in research and development projects, share costs, risks, and expertise to advance the next generation of advanced manufacturing and processing technologies. The U.S. Secretariat that facilitates the participation of U.S. participants is located in MEL. A description of the IMS program is included in this section.

In 1998, the MEL Management Council introduced a mechanism to encourage new areas of research – the MEL Exploratory Project. Each year, a small portion of laboratory funding is allocated for these projects to test the feasibility of a new idea or technology. Exploratory projects focus on topics that are within the mission of MEL, but outside the current scope of any current individual MEL or NIST strategic program. Exploratory Projects, typically lasting one year, experience varied outcomes. They could be deemed a success and brought to a natural conclusion at the end of the first year, they could be considered for expansion into a future strategic program, or they could be incorporated into an existing program.
A brief summary of the FY2002 Exploratory Projects is included in this section.

Intelligent Manufacturing Systems (IMS)

Program Contact:
Joan Wellington

Phone: 301 975-3564

Email:
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Program Funding: $370K

FTEs 1.0
(program administration)

Program Goal

The goal of the Intelligent Manufacturing Systems (IMS) program is to develop, in a coordinated worldwide effort, the next generation of manufacturing and processing technologies. The work is carried out through a series of industry-led international research and development (R&D) projects. The U.S. Secretariat that facilitates the participation of U.S. entities in the IMS program is located in MEL.

Customer Need

The next generation of advanced manufacturing and processing technologies will be expensive to produce. No single entity has all the expertise required. Cooperative R&D to share costs, risks, and expertise is necessary. Properly managed international cooperation in advanced manufacturing R&D through IMS can help improve manufacturing operations, enhance international competitiveness, and lead to technology breakthroughs via market-driven R&D.

Technical Approach

IMS technical activities are coordinated by the IMS Inter Regional Secretariat (IRS) with the assistance of a Regional Secretariat in each of the seven IMS regions. Entities from all regions – Australia, Canada, the European Union and Norway, Japan, Korea, Switzerland, and the United States – are eligible to collaborate on IMS projects. Each project must have participants from no less than three regions. The IMS program provides a support structure for conducting projects with specific arrangements for the protection of intellectual property rights (IPR). The protection of IPR enables small enterprises to cooperative effectively and on equal footing with larger ones.

IMS offers research institutions and academia the opportunity to work alongside the world's best researchers from industry to develop jointly the next generation of technology. The market-driven character of IMS R&D means that academics and researchers are part of an effort to transfer valuable technologies to future generations. The work of IMS is managed by an International Steering Committee (ISC) comprised of delegations from the member regions. The IRS carries out the work of the ISC. Industry, academia, and government agencies from all IMS regions as well as other manufacturing enterprises throughout the world are customers for the results of R&D done by IMS project partners.

Five technical themes provide the broad framework within which IMS projects operate. All projects must address one of more of the following technical themes

1. Total Product Life Cycle
   - Intelligent communication network systems for information processes in manufacturing;
   - Environmental protection;
   - Minimum use of energy and materials;
   - Economic justification methods.
2. Process
   - Energy efficient processes;
   - Technology innovation in manufacturing processes;
   - More flexibility and autonomy in processing modules that compose manufacturing systems.
3. Strategy/Planning/Design
   - Modeling tools to support the analysis and development of manufacturing strategies.
4. Human/Organization/Social
   - Improved corporate technical memory.
5. Virtual/Extended Enterprise
   - Information processes and logistics across the value chain;
   - Business, functional and technical architectures in support of engineering cooperation;
   - Concurrent engineering across the extended enterprise.

The average length of an IMS project from beginning to completion is three years. Currently more than 550 companies and research institutions including over 100 from the U.S. are active in IMS research consortia.

Program Objectives and Technical Outputs

Objective 1:

Enable greater sophistication in manufacturing operations and improve the global environment by improving the efficiency with which renewable and non-renewable resources are used.

Technical Outputs

FY2003:
Complete Phase II of Next Generation Manufacturing Systems (NGMS) Project that defines the scope of the "Digital Factory." Project results have already shown that by implementing the concepts of the Digital Factory, companies can save up to 30% in the factory start-up and operations.

FY2003:
Launch Phase III of NGMS project. This phase will use approaches such as virtual reality, biological or self-organizing manufacturing, fractal concepts and open communication standards to develop additional manufacturing strategies.

Objective 2:

Create new products and conditions that significantly improve the quality of life for users.

FY2003:
Seek additional U.S. partners for the AEMS (Advanced Environmental Monitoring System for Production Facitilites) IMS Project. This project will develop a groundwater monitoring system that will provide manufacturers with an effective tool for environmental protection and resource conservation and manage the risk of ground water contamination.

FY2003:
Assist U.S. entities in creation of additional IMS projects that improve the quality of life.

Objective 3:

Develop a recognized and respected discipline of manufacturing that will encourage the transfer of knowledge to future generations.

FY2003:
Continue development of IMS GEM (Global Education in Manufacturing) Project. The goal of this project is to create a world-recognized program that grants a master's degree in manufacturing engineering.

...the portal to global collaborative manufacturing Research and Development

Anticipated Impact

IMS is the first worldwide program to address manufacturing challenges and sustainable production systems in the 21th century. The IMS ISC has identified four guiding philosophies for IMS efforts in the next few years. These philosophies are:

- Enable industry to contribute to global wealth creation by addressing the value of information and knowledge and by exploiting emerging and converging technologies.
- Address synchronicity between technology and human needs taking into account the changing nature of the workforce and workplace and contributing to the development and certification of skills.
- Be agents for global equity and raised living standards worldwide through appropriate sharing of knowledge and diffusion of manufacturing knowledge.
- Enhance sustainability and resource efficiency in worldwide delivery of products and associates through process improvements adding greater intangible value and logical efficiency/business re-organization.

The program was fully endorsed in mid-1997 and since most projects require a minimum of three years to complete and many are choosing to add a second phase, results of early projects are just beginning to be realized. They do indicate that the anticipated impact of the program will be achieved.

Accomplishments of the Past Year

Five new IMS projects were endorsed during FY2002 and five were completed and are preparing final reports. Three additional projects completed their first phase of R&D and have begun a second phase. Total value of endorsed IMS projects is $250,000,000.00 U.S.

The IMS Inter Regional Secretariat was successfully relocated to the United States from Japan in June 2002. Mr. Kevin Levin manages the day-to-day operations of the IRS.

The first meeting of the International IMS Steering Committee hosted by the U.S. was held November 15-16, 2002, in Washington, DC. Mr. Robert Cattoi, Rockwell International (retired), assumed the chairmanship of the ISC upon its move to the U.S.

The working group established to plan the next phase of the IMS program has been established and held its first meeting immediately before the November ISC meeting. It will present a framework for the next phase of the IMS program to the Steering Committee in November 2003. The next phase of the program is scheduled to begin in April 2005.

Workshops

The International IMS Project Forum 2001 was held October 8-10, 2001 in Ascona, Switzerland. The forum was an initiative of of the IMS International Steering Committee and the Project Co-ordinating Partners, the over-all project managers, to create a common platform for cross-fertilization and exchange of experience among IMS projects. The forum continued the promotion of the IMS program worldwide. Another workshop of this type is planned for fall 2002.

NIST Participation in IMS Projects

Technical staff of MEL's Manufacturing Systems Integration Division (MSID) participated in and led the U.S. effort in the IMS MISSION (Modeling and Simulation Environments for Design, Planning and Operation of Globally Distributed Enterprises) project. Staff of the Manufacturing Simulation & Modeling Group (MSG) carried out the technical work and its Group Leader, Charles McLean, served as the U.S. Regional Coordinator for the project. Except for issuing the final report, this project has been completed and MSG has agreed to participate with the the group that will develop the full proposal for the recently-endorsed Network of Excellence IMS abstract.

Technical staff of NIST's Electronics and Electrical Engineering Laboratory participate in the IMS NGMS project mentioned earlier in this write-up.

For further information on IMS, check the IMS website (www.ims.org).

FY2002 Exploratory Projects

During the FY2002 competition, 19 staff members representing all of MEL's divisions submitted six Exploratory Project proposals. Three of the proposals were funded: Metrology for Meso Machine Tools, The Artificial Synapse, and Performance Analysis of Next Generation LADAR (NGL) for Automation in Manufacturing Metrology. Goals, accomplishments, and plans for follow-on work are described below for each of these three projects.

Metrology for Meso Machine Tools
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The Artificial Synapse
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Performance Analysis of Next Generation LADAR (NGL) for Automation in Manufacturing Metrology
Maris Juberts
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Metrology for Meso Machine Tools

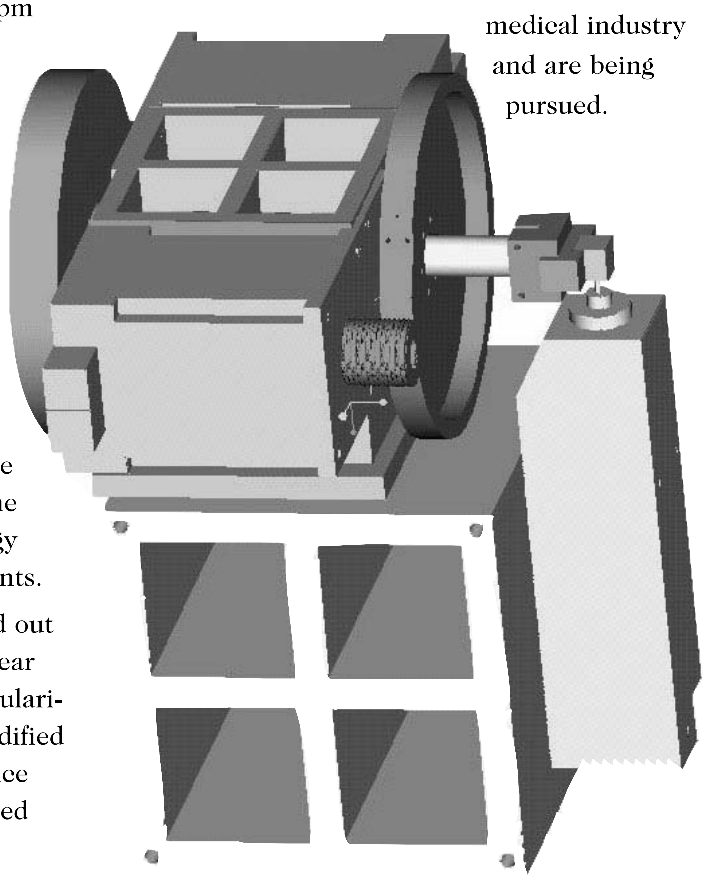
This exploratory project addressed the challenges and opportunities of metrology for a new generation of meso machine tools. Meso machine tools are small fabrication instruments that operate within work volumes (sub-millimeter-to-centimeter scale) to produce parts with critical feature sizes on the micrometer-to-millimeter scale. The original goal was, in collaboration with Hardinge Inc. and the Massachusetts Institute of Technology (MIT), to develop a meso-scale test platform to investigate the metrology alternatives that can be incorporated into such machines. Optimized design of machine tools for micro-meso fabrication would result in significant cost savings for industry. Such optimization would likely mean designing the machines to be much smaller, just like the parts, which would result in not only greatly reduced material and drive system cost, but also higher performance because the machines could be more easily isolated from the environment and have a smaller structural loop.

Internal Hardinge budget restrictions prevented the company from joining the development effort. Nevertheless, MEL staff carried out the design, engineering and fabrication of the MIT conceptual design for a low-cost multi-axis meso machine platform, called the Mesomill. In a parallel effort, the project staff collaborated with Heidenhain Corp. to develop an alternative machine platform utilizing a 2-dimensional (2D) grid encoder for direct position feedback. In addition, MEL staff designed a metrology frame that was incorporated into an existing desktop milling machine to demonstrate the advantages of small machines for such applications.

In summary, the project team accomplished the following:

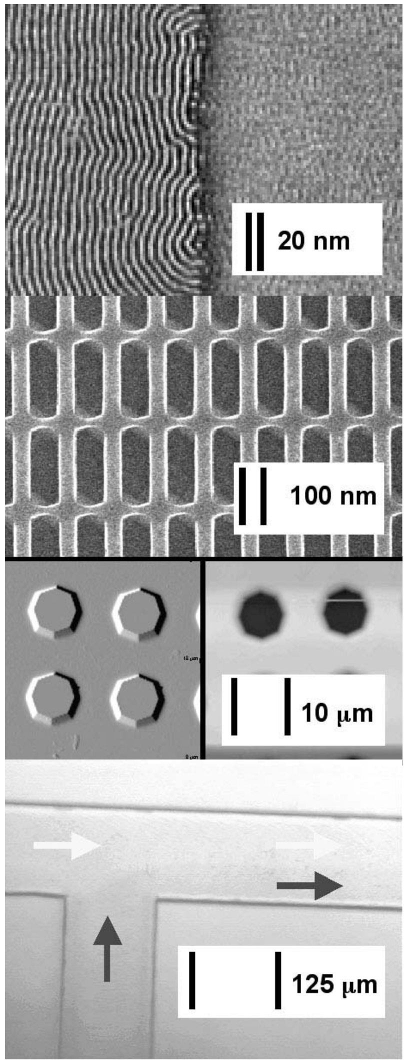
- Completed the design, engineering, fabrication and assembly of the Mesomill — a three-axis meso-scale milling machine. This design utilizes novel components such as combination rotary/linear axes, wire-drive capstan drives, and a new z-encoder capable of simultaneously measuring both linear and rotary movement. Performance tests, including cutting experiments, are planned following the completion of wiring.
- Carried out an error budget analysis for this design; results indicate that a 1.5 mm tool path error can be expected within the machine volume.
- Obtained on loan from ESI Corp a 130,000 rpm air-bearing spindle and integrated it with the machine base. This spindle has a voice-coil linear actuator to provide z-axis motion. Specific metrology challenges related to small, ultra-high speed spindles were identified and are being investigated.
- Submitted two abstracts to the American Society of Precision Engineering for the January 2003 topical meeting on machines and processes for micro-scale and meso-scale fabrication, metrology, and assembly. The first abstract is for a paper describing the design and development of this machine. The second is for a paper describing the metrology frame and resulting performance improvements.
- In collaboration with Heidenhain Co., carried out the preliminary performance tests on the linear actuator based 2D motion platform. The circularity error was measured to be 0.6 mm. We modified the original design to improve the performance further. Heidenhain is fabricating the modified platform that will be delivered to MEL.
- Completed baseline performance evaluation on the tabletop milling machine. These results will be used to compare the performance improvements from to the original system to one that uses an integrated metrology frame.
- Designed a metrology frame for the tabletop milling machine. The final design modifications are currently being completed and will be submitted to MEL's Fabrication Technology Division for fabrication.
- Developed an invention disclosure for a possible patent on the metrology frame.

In collaboration with NIST Industrial Liaison Office, the MEL staff has begun investigating how new-generation meso machine tools might help the medical apparatus manufacturers. In July 2002, the project staff presented its plans and accomplishments during the Orthopedic Surgical Manufacturers Association meeting and received very positive feedback. As a result, contacts were identified in the medical industry and are being pursued.



Solid model of the Mesomill prototype

The Artificial Synapse



Microfluidic devices—miniaturized “laboratories on a chip”—hold great promise for increasing the speed and reducing the costs of chemical reactions. However, a number of manufacturing challenges need to be addressed. This exploratory project focused on the connections (or synapses) between different device levels and scales. Nanoscale, chemically functionalized templates need to be embedded within microfluidic devices as essential links between the scale at which molecular recognition and self-organization occurs and the macroscopic layout of fluid channels, mixing volumes, and detection regions of analytical systems.

The project focused on the fabrication of a prototype system for investigating coupled oscillating chemical reactions far from equilibrium, and resulted in newfound expertise in nanolithography, nanoimprint lithography, and microfluidics. In addition, it led to a broader multidisciplinary collaboration involving MEL’s Precision Engineering, Manufacturing Metrology, and Fabrication Technology divisions as well as the NIST Material Science and Engineering Laboratory (MSEL) Center for Combinatorial Methods. The goal of this effort is the standardization of manufacturing procedures for microfluidic devices.

Examples from recent work illustrate the dimensional range of the structures that are incorporated into microfluidic devices: 1) surface-directed assembly of copolymer domains (top panel); 2) use of scanning probe lithography (SPL) and anisotropic etching to produce nanoarrays in a silicon master (upper middle panel); 3) replication of silicon arrays produced by optical lithography and SPL into polyvinyl-chloride (PVC) films by hot embossing and in polydimethol-siloxane (PDMS) by casting (lower middle panel); and 4) the development of a generic microfluidic experimental platform that orients 125 µm channels embossed in a polyvinyl chloride (PVC) gasket to an array of high-speed machined channels and a silicon substrate or PVC replica (bottom panel). Efforts are now under way to leverage progress made during this exploratory project into a competence project to support scientifically as well as industrially relevant microfluidics applications.

Further information about this project may be found in the following:

Schmitz, T. L.; Dagata, J. A.; and Dutterer, B., Nanolithography and Microfluidics: A Manufacturing Perspective, CIRP 2003 Meeting Abstract, submitted.

Harrison, C.; Dagata, J. A., Lithography with Self-assembled Copolymer Microdomains, in Self-Assembly (tent.), Hamley, I., ed., (John Wiley, NY, 2003), in preparation.

Chien, F.S.; Hsieh, W.F.; Gwo, S; A. E. Vladar; Dagata, J.A., Silicon Nanostructures Fabricated by Scanning Probe Oxidation and Tetra-methyl Ammonium Hydroxide Etching, J. Appl. Phys. 91; 10044; 2002

Performance Analysis of Next-Generation LADAR (NGL) for Automation in Manufacturing Metrology

The commercial development and application of 3-dimensional (3D) range imaging systems is growing rapidly. The use of laser detecting and ranging (ladar) for topographic and other types of mapping is growing at a rate of 25 percent per year. One report estimates that, in 10 years, ladar will replace traditional field survey instruments used in construction. In addition, ladar use is growing in inspection, automation, and safety and crash avoidance applications in the automotive and aerospace industries. Hundreds of ladar products exist; however, it is difficult, if not impossible, to find information about measuring specifications, calibration, and uncertainty in the product descriptions. There are no standards, and the industry is looking to NIST for technical leadership. Unresolved issues that limit the emergence of ladar technology include lack of traceability, high cost, large size and the need for robust post-processing software.

The project team planned to conduct an assessment of laser-based range measurement technology to determine the feasibility of developing a next-generation 3D range-imaging sensor that could be used in support of a proposed NIST multi-laboratory initiative to develop a prototype 3D range and standards facility or other such facilities.

The project had five objectives:

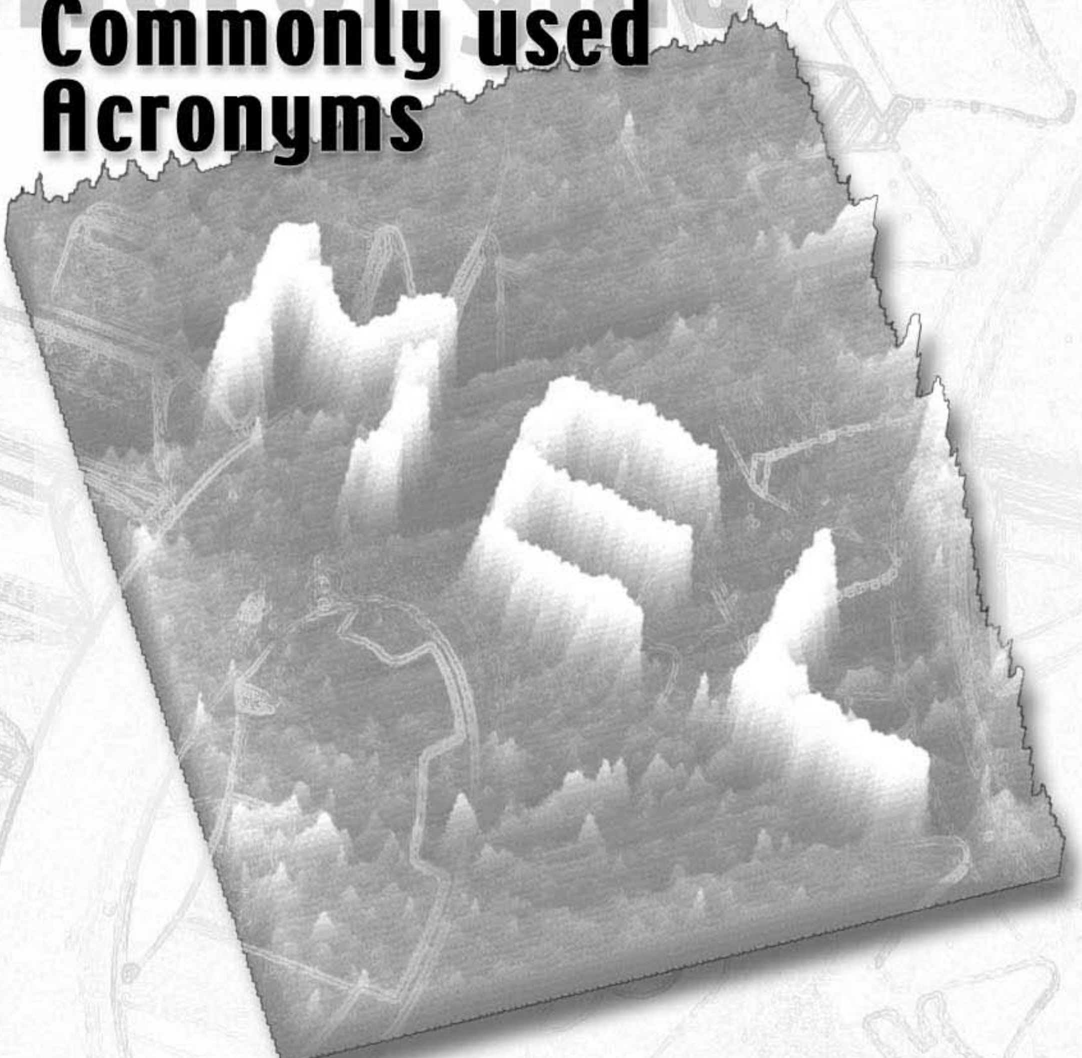
1. determine manufacturing industries' calibration needs;
2. evaluate the latest capabilities and measurement methods used in ladar-based range measurement technology;
3. investigate possible solutions for achieving mm/sub-mm range measurement accuracy using existing or advanced ladar-based range measurement technology;
4. in collaboration with the NIST Building and Fire Research Laboratory (BFRL), gather experience with calibration of active/passive optical sensors; and
5. propose an approach for the development of a next generation ladar (NGL) system for the 3D range imaging metrology initiative in collaboration with the goals and objectives of the joint partnership with NIST's Physics, Electronic and Electrical Engineering, and Building and Fire Research laboratories.

The project team made good progress toward meeting their objectives. The team members visited many of the leading ladar researchers and developers throughout the United States and Europe. Unfortunately, due to the September 11, 2001 terrorist attacks, the team did not get to visit as many places as originally planned. Even so, they discovered that development activities in NGL are much broader than originally thought. The team gained invaluable information and competence in this emerging field. In fact, the knowledge gained from this project helped one of the team members prepare a NIST Broad Agency Announcement (BAA) that included requirement specifications for the design of a NGL for autonomous unmanned ground vehicles – in support of the Army-sponsored Demo III Unmanned Ground Vehicle program.

Other accomplishments included the following:

- Four contracts were awarded for the design of engineering prototype sensors.
- PMDTec Inc., of Germany, conducted a concept study for building a low cost CMOS (complementary metal oxide semiconductor) – based Focal Plane Array (FPA) detector for the construction and manufacturing industries. The report covers possible sensor solutions for control of machines in construction and manufacturing, large-area metrology applications, and safety applications in automobiles or trucks for crash avoidance.
- Ladar developers provided information on their manufacturing industries' metrology needs; however, the team was unable to determine those needs for the leading users (such as Boeing and the National Aeronautics and Space Administration, or NASA). The team plans to obtain contacts within the user community to survey their metrology needs.
- The team identified the following areas as those having a good potential for possible ladar applications:
  - automation and robot control for industry use
  - industrial inspection for automotive, aircraft, and building industries
  - ground vehicle and aircraft guidance (military and transportation industry)
  - smart munitions and fire control (military)
  - medical applications (3D digitization of teeth, bones during surgery and for tele-surgery)
  - entertainment and retail
- The MEL and BFRL team members plan to publish a final report on this study that will propose steps for NIST to take in identifying the needed technologies and ways to achieve the basic sensor requirements. Toward this end, team members Bill Stone (BFRL) and Maris Juberts (MEL) jointly authored a paper, " Toward the Ultimate Construction Site Sensor," which was presented at the BFRL-sponsored International Symposium on Automation and Robotics in Construction 2002 Conference held at NIST in September 2002.

Commonly used Acronyms



A2LA	American Association for Laboratory Accreditation
AAAI	American Association for Artificial Intelligence
AAMACS	Advanced Automated Master Angle Calibration System
ACM	Association for Computing Machinery
ADACS	Advanced Deburring and Chamfering System
ADL	Architecture Design Language
AE	Acoustic Emission
AE	Acoustical Emission
AECMA	The European Association of Aerospace Industries
AFM	Atomic Force Microscope, Atomic Force Microscopy
AFMETCAL	Air Force Metrology and Calibration Program
AGA	American Gas Association
AGMA	American Gear Manufacturers Association
AGV	Automated Guided Vehicle
AIAG	Automotive Industry Action Group
AIM	Application Interpreted Model
AIMS	Agile Infrastructure for Manufacturing Systems
AMSANT	Advanced Manufacturing Systems Applications Networked Testbed
AMT	Association for Manufacturing Technology
AMWA	Association for Metropolitan Water Agencies
ANN	Artificial Neural Network
ANSI	American National Standards Institute
AP	Application Protocol
APDE	Application Protocol Development Environment
APEC	Asian Pacific Economic Cooperation
API	American Petroleum Institute or Application Programming Interface
APMP	Asia-Pacific Economic Cooperation
ARL	Army Research Laboratory
ARM	Application Reference Model
ASA	Acoustical Society of America
ASACOS	Acoustical Society of America Committee on Standards
ASCII	American Standard Code for Information Interchange
ASME	American Society of Mechanical Engineers
ASPE	American Society of Precision Engineers

ASRS	Automated Storage and Retrieval Systems
ASTM	American Society for Testing and Materials (now called ASTM)
ATEP	Algorithm Testing and Evaluation Program
ATM	Asynchronous Transfer Mode
ATP	Advanced Technology Program
ATR	Advanced Technology and Research
ATS	Abstract Test Suite (related to STEP) or Algorithm Testing System
AWMS	Automated Welding Manufacturing System
AWS	American Welding Society
B2B	Business-to-Business
B2B2C	Business-to-Business-to-Consumer
B2C	Business-to-Consumer
BCAC	Boeing Commercial Airplane Company
BFRL	Building and Fire Research Laboratory
BIPM	Bureau International des Poids et Mesures (France)
BITWO	Best in the World
BMP	Best Manufacturing Practices program
CAD	Computer Aided Design
CAE	Computer Aided Engineering
C-AFM	Calibrated Atomic Force Microscope
CAID	Computer-Aided Industrial Design
CALS	Continued Acquisition and Life Cycle Support
CAM	Computer Aided Manufacturing
CAME	Computer Aided Manufacturing Engineering
CAM-I	Consortium for Advanced Manufacturing - International
CAPP	Computer Aided Process Planning
CASE	Computer-Aided Software Engineering
CBM	Condition Based Maintenance or Condition Based Monitoring
CBN	Cubic Boron Nitride
CC	Consultative Committee or common criteria
CCAUV	Comité Consultatif de l'Acoustique, des Ultrasons et des Vibrations
	Consultative Committee for Acoustics, Ultrasound and Vibration
CCD	Charge-Coupled Device
CCM	Consultative Committee on Mass and Related Quantities
CD	Critical Dimension, Committee Draft, or Compact Disk

CEN	European Committee for Standardization
CENAM	Centro Nacional de Metrologia (Mexico)
CGPM	General Conference of Weights and Measures
CID	Charge Injection Device
CIFP	Capital Improvement of Facilities Project
CIM	Computer Integrated Manufacturing
CIMOSA	Computer Integrated Manufacturing Open Systems Architecture
CIPM	International Committee of Weights and Measures (France)
CIRP	College International Pour l Etude des Techniques de Production Mecanique
	(International Organization for Production Engineering Research)
CMM	Coordinate Measuring Machine
CMP	Chemical-Mechanical Polishing
CMS	Coordinate Measuring System
CNC	Computer Numerical Control
COGM	Committee on Gear Metrology (ASME)
COM	Component Object Model
COOMET	Euro-Asian Cooperation Of National Metrological Institutions
CORBA	Common Object Request Broker Architecture
CPM	Core Product Model
CRADA	Cooperative Research and Development Agreement
CSIRO	Commonwealth Scientific and Industrial Research Organization (Australia)
CSTL	Chemical Science and Technology Laboratory
CXO	Chandra X-ray Observatory
DAIS.	Data Acquisition from Industrial Systems
DAML	DARPA Agent Markup Language
DARPA	Defense Advanced Research Projects Agency
Dasa	DaimlerChrysler Aerospace
DB	Database
DBMS	Database Management Systems
DCOM	Distributed Component Object Model
DCS	Distributed Control Systems
DETC/CIE	Design Engineering Technical Conference/Computers in Engineering
DFM	Danish Institute of Fundamental Metrology (Denmark)
DFM	Design For Manufacture
DFT	Design for Tolerancing

DIS	Draft International Standard
DLL	Dynamic Link Libraries
DMIS	Dimensional Measuring Interface Standard
DMS	Distributed Manufacturing Simulation
DMSO	Defense Modeling and Simulation Office
DNC	Direct Numerical Control
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOT	DMIS Object Technology or Department of Transportation
DSP	Digital Signal Processors
DTD	Document Type Definition
DTM	Diamond Turning Machine
DTRA	Defense Threat Reduction Agency
DVM	Digital Voltmeter
E^2M	Economically driven Environmentally conscious Manufacturing
EAL	European Cooperation for Accreditation of Laboratories
ECD	Electrical Critical Dimension
ECSS	Expert Control System Shell
EDI	Electronic Data Interchange
EDM	Electrical Discharge Machining
EEEL	Electronics and Electrical Engineering Laboratory
EIA	Electronic Industries Alliance
	(changed from Electronic Industries Alliance in 1997)
EIF	Enterprise Integration Framework
EMC	Enhanced Machine Controller
EMI	ElectroMagnetic Interference
EMMA	Easily Manipulated Mechanical Armature
EMS	Electronics Manufacturing Service
EPISTLE	European Process Industries STEP Technical Liaison Executive
EPRI	Electric Power Research Institute
ERM	Enterprise Resource Management
ERP	Enterprise Resource Planning
ETL	Electrotechnical Laboratory

EU	European Union
EUROMET	European Collaboration in Measurement Standards
EUSPEN	European Society for Precision Engineering and Nanotechnology
EUVL	Extreme Ultraviolet Lithography
FAMU	Florida Agricultural and Mechanical University
FBICS	Feature Based Inspection and Control System
FCIM	Flexible Computer Integrated Manufacturing
FDIS	Final Draft International Standard
FEA	Finite Element Analysis
FEM	Finite Element Modeling
FHWA	Federal Highway Administration
FIM	Field Ion Microscopy
FIPA	Foundation for Intelligent Physical Agents
FIPS	Federal Information Processing Standard
FLIR	Forward Looking Infra-Red
FMR	Field Material-handling Robot
FOT	Field Operations Test
FSU	Florida State University
FTD	Fabrication Technology Division
FTP	File Transfer Protocol
FY	Fiscal Year (October 1 - September 30)
GDP	Gross Domestic Product
GDRS	General Dynamics Robotic Systems
GD&T	Geometric and Dimensional Tolerancing
GERAM	General Enterprise Reference Architecture Model
GIF	Graphics Interchange Format
GMAW	Gass Metal Arc Welding
GOALI	Grant Opportunities for Academic Liaison with Industry (NSF program)
GPL	General Purpose Laboratory
GPS	Global Positioning System or Geometric Product Specification
GUI	Graphical User Interface
GUM	ISO Guide to the Expression of Uncertainty in Measurements
HLA	High Level Architecture
HMMWV	High Mobility Multipurpose Wheeled Vehicle
HPCC	High Performance Computing and Communications

HRC	Rockwell C Hardness
HTML	HyperText Markup Language
HTTP	Hyper Text Transfer Protocol
IAI	Industry Alliance for Interoperability
IAMS	Institute of Advanced Manufacturing Sciences
IAV	Industrial Autonomous Vehicle
IBIS	Integrated Ballistics Identification System
IC	Intelligent Control, International Comparison, or Integrated Circuit
ICM	Internet Commerce for Manufacturing
IDEF	Integrated Computer-Aided Manufacturing Definition
IDL	Interface Definition Language
IE	Industrial Engineering, Invested Equipment
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IFIP	International Federation for Information Processing
IGES	Initial Graphics Exchange Specification
IGRIP	Interactive Graphics Robot Instruction Program
IGT	Institute for Gas Technology
IITA	Information Infrastructure Technology Applications (HPCC program)
IMES	Initial Manufacturing Exchange Specification
IMES	Initial Manufacturing Exchange Specification
IMGC	Instituto di Metrologia G. Colonnetti (Italy)
IMS	Intelligent Manufacturing Systems
IMTI	Integrated Manufacturing Technology Initiative
IMTR	Integrated Manufacturing Technology Roadmap (http://imtr.ornl.gov/)
IMU	Inertial Measurement Unit
INAOE	Instituto Nacional de Astrofisica, Optica, y Electr nica in Tonantzinla, Puebla, Mexico
INMETRO	Instituto Nacional de Metrologia, Normalizacao e Qualidade Industrial (Brazil) Brazilian National Measurement Institute in Rio de Janeiro
INS	Inertial Navigation System
IP	Internet Protocol
IPM	Intelligent Processing of Materials
IPO	IGES/PDES Organization
IPR	In Process Review
IR	Infrared (light)

IS	International Standard
ISAM	Indexed Sequential-Access Management/Method
ISATP	International Symposium on Assembly and Task Planning
ISD	Intelligent Machines Division
ISIC/CIRA/ISAS	Three combined conferences: IEEE International Symposium on Intelligent Control, IEEE International Symposium on Computational Intelligence in Robotics and Automation, and the Intelligent Systems and Semiotics conference
ISMT	International SEMATECH
ISO	International Organization for Standardization —
	not an acronym according to ISO
ISOMA	International Symposium on Manufacturing and Applications
ISPE	International Society for Pharmaceutical Engineering
IT	Information Technology or Industrial Technology
ITA	Interim Testing Artifact
ITL	Information Technology Laboratory
ITRS	International Technology Roadmap for Semiconductors
ITS	Intelligent Transportation Systems
ITU	International Telecommunication Union
JAST	Joint Advance Strike Technology (a DOD program)
JAUGS	Joint Architecture for Unmanned Ground Vehicle Systems (DOD)
JCGM	Joint Committee for Guides in Metrology
JEDMICS	Joint Engineering Data Management Information Computer Systems
JPEG	Joint Photographic Experts Group
JPL	Jet Propulsion Laboratory
JSW	Joint Standards Workshop
KEMAR	Knowles Electronics Manikin for Acoustic Research
KIC	Key International Comparison
KIF	Knowledge Interchange Format
KRISS	Korea Research Institute of Standards and Science
LARCS	Laser Rail Calibration System
LDWS	Lane Departure Warning Systems
LFAD	Laser-Focused Atomically Deposited
LIGO	Laser Interferometric Gravitational-wave Observatory
LLNL	Lawrence Livermore National Laboratory
LM	Layered Manufacturing

LMT	Large Millimeter Telescope
LSI	Line Scale Interferometer
LVDT	Linear Variable Differential Transformer
M2A	Manipulation, Measurement, and Assembly
M^3	Molecular Measuring Machine
MAA	Metrology Automation Association
MADE	Manufacturing Automation Design Engineering Project (a DARPA project)
MANTECH	Manufacturing Technology (a DOD program)
MAP	Measurement Assurance Program
MBE	Molecular Beam Epitaxy
MCITT	Manufacturer s CORBA Interfact Testing Toolkit
MEL	Manufacturing Engineering Laboratory
MELSA	MEL System Administration team
MEMS	Micro-electromechanical systems
MEP	Manufacturing Extension Partnership
MES	Manufacturing Execution System
METK	Manufacturing Engineering Tool Kit
MfgDTF	Manufacturing Domain Task Force (OMG)
MfgTF	Manufacturing Task Force (an OMG program)
MFPT	Society for Machinery Failure Prevention Technology
MIDMAP	Mid-America Measurement Assurance Program regional grouping of U.S. state metrology labs for national key comparisons
MISSION	Modeling and Simulation Environments for Design, Planning and Operation of Globally Distributed Enterprises
MITT	Manufacturing Information Technology Transfer
MOB	Mobile Offshore Base
ModSAF	Modular Semi-Automated Forces, a standard military simulation tool
MPA NRW	Materialpr fungsamt Nordrhein—Westfalen (Germany)
MR	Manufacturing Resource
MRD	Materials Reliability Division (NIST Materials Science and Engineering Laboratory)
MRP	Material Requirements/Resource Planning
MSA	Microscopy Society of America
MSEL	Materials Science and Engineering Laboratory
MSI	Manufacturing Systems Integration
MSID	Manufacturing Systems Integration Division

MTBF	Mean Time Between Failures
MWG	Technical Working Group under SIM
NADC	Naval Air Development Center
NAMAS	National Measurement Accreditation Service (England)
NAMT	National Advanced Manufacturing Testbed
NASA	National Aeronautics and Space Administration
NSA	National Security Agency
NAVLAP	National Voluntary Laboratory Accreditation Program
NC	Numerically controlled (machine tools and equipment)
NCAP	Network Capable Application Processor
NCMS	National Center for Manufacturing Sciences
NCS A&T	North Carolina State Agricultural and Technical University
NCSL	National Conference of Standards Laboratories
NDE	Non-Destructive Examination
NEMAP	Northeast Measurement Assurance Program regional grouping of U.S. state metrology labs for national key comparisons
NEMS	nanoelectromechanical systems
NGIS	Next Generation Inspection System
NGM	Next Generation Manufacturing
NHTSA	National Highway Traffic Safety Administration
NIAP	NIST/NSA National Information Assurance Partnership
NICS	NIST Identifier Collaboration Service
NIF	National Ignition Facility
NII	National Information Infrastructure
NIIIP	National Industrial Information Infrastructure Protocols
NIJ	National Institute of Justice
NIM	National Institute of Metrology (China)
NIST	National Institute of Standards and Technology
NISTIR	National Institute of Standards and Technology Interagency/Internal Report
NIST-IR	NIST Industrial Robot
NITS	NIST - ITI Test System
NMI	National Metrology (Measurement) Institute
NORAMET	North American Metrology Cooperation
	(with NRC of Canada and CENAM of Mexico)
NPL	National Physical Laboratory (U.K. or India)

NRC	National Research Council (U.S. and Canada)
NRL	Naval Research Laboratory
NRLM	National Research Laboratory of Metrology (Japan)
NRO	National Reconnaissance Office
NSA	National Security Agency
NSF	National Science Foundation
NSRP	National Shipbuilding Research Program
NTA	National Technical Association
NTEP	National Type Evaluation Program
NTRS	National Technology Roadmap for Semiconductors
NVLAP	National Voluntary Laboratory Accreditation Program
OA	Other (government) Agency
OAC	Open Architecture Control
OAG	Open Applications Group
OAGIS	Open Applications Group Integration Specification
OAS	Organization of American States
OASIS	Organization for the Advancement of Structured Information Standards
OEM	Original Equipment Manufacturer
OEOSC	Optics and Electro-Optics Standards Council
OI	Operator Interface
OIDA	Optoelectronics Industry Development Association
OIML	Organization Internationale de Metrologie Legale International Organization of Legal Metrology
OLES	Office of Law Enforcement Standards (NIST)
OMA	Object Management Architecture
OMAC	Open Modular Architecture Controller
OMG	Object Management Group
OMP	Office of Microelectronics Programs
OpenADE	Open Assembly Design Environment
ORB	Object Request Broker
ORMC	Oak Ridge Metrology Center
OSD	Office of the Secretary of Defense
OSRM	Office of Standard Reference Materials
OWL	Web Ontology Language
OWM	Office of Weights and Measures (NIST)

PAC	Personal Air Conditioning
PC	Printed Circuit or Personal Computer
PCMCIA	Personal Computer Memory Card International Association
PCSRF	Process Control Security Requirements Forum
PDES	Product Data Exchange Using STEP
PDM	Product Data Management
PED	Precision Engineering Division
PKM	Parallel Kinematic Machines
PL	Physics Laboratory
PLC	Programmable Logic Controllers
PLM	Polarized Light Microscopy
PMI	Phase Measuring Interferometer
POAC	Precision Optoelectronics Assembly Consortium
POSC	Petrotechnical Open Software Corporation
PRT	Platinum Resistance Thermometer
PSD	Power Spectral Density
PSL	Process Specification Language or Problem Statement Language
PTB	Physikalisch-Technische Bundesanstalt (Germany)
Pt-Ir	Platinum Iridium
PVDF	Polyvinylidenefluoride
PWI	Preliminary Work Item
PZT	A ceramic piezo-electric material used in actuators and ultrasonic
Q&V	Qualification and Validation
QIA	Quality In Automation
R&D	Research and Development
RaDEO	Rapid Design Exploration and Optimization program
RAMM	Rapid Agile Metrology for Manufacturing (an ATP sponsored program)
RAMP	Rapid Acquisition of Manufactured Parts (a DoD sponsored program)
RCS	Real-Time Control System
RCSA	Receptance Coupling Substructure Analysis
RDF	Resource Description Framework
RFP	Request For Proposals
RIA	Robotics Industries Association
RM	Research Material
RMS	Root Mean Square

ROI	Return On Investment
RP	Rapid Prototyping
RRL	Rapidly Renewable Lap
RRM	Rapid Response Manufacturing
RSS	Root Sum Squares
RST	Robot Systems Technology
RSTA	Reconnaissance, Surveillance, and Target Acquisition
RTI	Run-Time Infrastructure or Real Time Innovations, Inc.
SAE	Society of Automotive Engineers
SAIC	Science Applications International Corporation
SBIR	Small Business Innovation Research
SC	Subcommittee (under ISO)
SCADA	Supervisory Control and Data Acquisition
SCLD	Scanning Capacitance Line Detector
SDAI	Standard Data Access Interface
SDX	Simulation Data Exchange
SEI	Software Engineering Institute at Carnegie Mellon University
SEM	Scanning Electron Microscope, Scanning Electron Microscopy
SEMAP	Southeast Measurement Assurance Program regional grouping of U.S. state metrology labs for national key comparisons
SEMATECH	SEmiconductor MAnufacturing TECHnology consortium (formally changed to International SEMATECH in 2000)
SEMI	Semiconductor Equipment and Materials International
SET	Single Electron Tunneling
SFF	Solid Freeform Fabrication
SGML	Standard Generalized Mark-up Language (an ISO standard)
SI	Systeme Internationale d Unites (the modern metric system)
SIA	Semiconductor Industry Association
SIF	Solid Interchange Format
SIGMA	Supersonic Inert Gas-Metal Atomizer
SIM	Systema Interamericano de Metrologia;
	Interamerican System of Metrology (English translation)
SIMA	Systems Integration for Manufacturing Applications
SIMOX	Separation by Implantation of Oxygen
SIP	STEP Implementation Prototype

SLA	Stereolithography apparatus
SME	Small/Medium Enterprise
SOI	Silicon-On-Insulator
SOLIS	SC4 On-Line Information Services
SPIE	The International Society for Optical Engineering
SPM	Scanning Probe Microscopy, Scanning Probe Microscope
SQL	Standard Query Language
SRM	Standard Reference Material
STEP	STandard for the Exchange of Product model data
STL	Stereolithography
STM	Scanning Tunneling Microscope, Scanning Tunneling Microscopy
STRS	Scientific and Technical Research and Services (NIST appropriated budget)
STS	Scanning Tunneling Spectroscopy
SWAP	Southwest Measurement Assurance Program regional grouping of U.S. state metrology labs for national key comparisons
SXPL	Soft X-ray Projection Lithography
TACS	Tactical Auxiliary Crane Ship
TAG	Technical Advisory Group
TC	Technical Committee (under ISO)
TCP	Transmission Control Protocol
TDP	Technical Development Plan, Technical Data Package
TEAM	Technologies Enabling Agile Manufacturing (DOE)
TEDS	Transducer Electronic Data Sheet
TEM	Transmission Electron Microscope, Transmission Electron Microscopy
TIDE	Technology Insertion, Demonstration, and Evaluation program of SEI
TIMA	Technologies for the Integration of Manufacturing Applications (ATP program)
TIMS	Testing of Interaction-driven Manufacturing Systems
TIS	Tool Induced Shift
TLM	Technology Learning Modules
UdeBW	Universitat de Bundeswehr (German)
UGV	Unmanned Ground Vehicle
UHV	Ultrahigh Vacuum
ULSI	Ultra Large Scale Integration
UML	Universal Modeling Language

UN/CEFACT	United Nations Centre for Trade Facilitation and Electronic Business
USNC	United States National Committee of IEC
USNWG	United States National Working Group
US TAG	United States Technical Advisory Group
USPRO	United States Product Data Association
UTAP	Unified Telerobotic Architecture Project
UTRC	United Technologies Research Center
UV	Ultraviolet (light)
VA	Department of Veterans Affairs
VIM	International Vocabulary of Basic and General Terms in Metrology
VLSI	Very-Large-Scale Integrated...
VRML	Virtual Reality Modeling Language
W	Tungsten
W&M	Weights & Measures
WG	Working Group
WGDM	Working Group on Dimensional Metrology
WRAP	West Region Measurement Assurance Program regional grouping of U.S. state metrology labs for national key comparisons
WWW	World Wide Web
XCALIBIR	X-ray Optics Calibration Interferometer
XML	Extensible Markup Language
XRT	X-ray Topography
XSLT	eXtensible Style Language for Transformations
XUV	Next Generation Unmanned Vehicle